PACIFIC MARINE SCIENCE REPORT 72-6

THE MOVEMENT OF FRASER RIVER-INFLUENCED SURFACE WATER IN THE STRAIT OF GEORGIA AS DEDUCED FROM A SERIES OF AERIAL PHOTOGRAPHS

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INTRODUCTION

The Strait of Georgia lies between Vancouver Island and the mainland coast of British Columbia and is one of a series of coastal seaways of major importance. A large amount of fresh water enters the Strait each year, mainly from stream and river discharges; more than three quarters of this amount is contributed by the Fraser River. Upon entry into the Strait the fresh Fraser River water tends to form a distinct surface layer-riding, and mixing with, the receiving saline sea water. In the vicinity of the river mouth this surface layer frequently appears as a jet (or plume, as it is commonly called). The transport and the extent of this surface plume are generally influenced by three primary factors - river runoff, wind, and tide, and by three secondary factors - Coriolis force, centrifugal force and topography.

In recent years, it has become increasingly apparent that more accurate information upon the behaviour of the plume, particularly its movement, is required. This need is associated with the growing population and increasing industrial activity in the lower mainland of British Columbia which have created a variety of problems ranging from the dispersal of domestic and industrial waste to the conflict between accelerated commercial and recreational uses of the Strait.

A comprehensive current velocity measurement survey, employing conventional shipborne techniques, requires considerable manpower and material resources; data coverage over a large area possessing sufficient synopticity make it a difficult task. Aerial photography or other remote sensing techniques such as infrared scanning, do however, provide alternate means of obtaining adequate information on the surface circulation over a wide area with suitable synopticity.

About two decades ago, aerial surveys were conducted over the eastern part of the Strait of Georgia in the region of the mouth of the Fraser River by the Greater Vancouver Sewerage and Drainage District as a basis for deciding on a suitable site for its major sewer outfall serving the Greater Vancouver District. Although the data collected from these surveys have been utilized to describe the movement of water in the nearshore areas on the eastern part of the Strait (Fjarlie, 1950), certain features of the photographs have not been discussed. The present report utilizes these unique data to give, essentially, a qualitative description of the surface flow in the central Strait of Georgia where it is affected by the Fraser River. The few isolated photographs taken previously and subsequently to 1950 have also been utilized to aid the interpretation of surface currents in the region.

It is to be noted that since 1950 some marine "obstructions" (Iona Jetty, and Tsawwassen Jetty) have been constructed (Fig. 1), while very recently another construction, the Roberts Bank Superport, has been started just north of the Tsawwassen Jetty. These will, no doubt, modify or affect the circulation of water in the immediate area of these constructions. However, unless they have direct bearing on the subject matter under discussion, little will be said about them.

AERIAL SURVEYS OF 1950

A total of 16 flights were made at about two-hourly invervals on the 1st, 9th and 10th of June, 1950. Seven of these flights were made between 0620 and 1820 hours, (Pacific Standard Time (PST)) on the 1st of June; two were made between 0640 and 0830 hours on the 9th of June and the remainder between 0600 and 1800 hours on the 10th of June. After about

two hours, the survey of 9th of June was postponed due to unsuitable weather.

The flight track for aerial photography started from a position about 4 miles west of Point Roberts and ended about one mile south of Bowen Island (Fig. 1). Additional photographs were taken along a track starting at a position about 3 miles south of Bowen Island to a point about 3 miles east of Second Narrows in Burrard Inlet.

Photographs were taken by the Air Survey Division of the Department of Lands, Forest, and Water Resources of British Columbia from an altitude of approximately 15,000 feet from a twin-engine Beachcraft Expeditor having a cruising speed of about 100 knots. Both vertical and oblique photography were employed simultaneously, the former covering a ground area of 16 square miles[1] (4 miles x 4 miles) along the flight track while the latter covered both sides along the track. Each successive photograph possessed a 60% overlap with the preceding one. The oblique photography was conducted with the optical axis of the camera, a Trimetrogon tri-camera (film size 5 inches x 5 inches), tilted 30° from the horizon.

It should be mentioned, that, while a series of overlapping vertical photographs can easily be used to exactly position water features with reference to land marks, it is much more difficult with oblique photographs since perspective distortion permitted only positions within several miles of the flight track to be determined accurately.

The first survey (1 June) was conducted during a period of large tides (Fig. 2a) while the second (9, 10 June) was made during a period of

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[1]All mileages in the present report are expressed in nautical miles.

small tides (Fig. 2b). Winds recorded at Vancouver International Airport on Sea Island were, during the first survey, from the northwesterly direction with speeds ranging from 12 to 17 knots (Table 1a) and during the second survey were from the same direction but were considerably smaller in magnitude (Table 1b). The Fraser River discharge, as measured at Hope, B.C. located about 100 miles inland, was about 200,00 ft^3/sec during the surveys (Fig. 3).

Also available are a pair of oblique photographs taken over the general area on 5th of June, 1948 a time of a large Fraser River runoff of 450,000 ft^3/sec (Fig. 3) and flooding in the Fraser Valley. These photographs further coincided with the flood of a large tide (Fig. 2c) when winds were from the northwest with speeds of up to 11 knots (Table 1c).

Some more recent photographs, taken with a hand-held 35 mm camera (Nikon F) from a helicopter at an altitude of about 1000 feet, are available for the 4th of June, 1968. These coincided with the ebb of a small tide (Fig. 2d) and a Fraser River discharge of about 300,000 ft^3/sec (Fig. 3).

BACKGROUND OCEANOGRAPHIC INFORMATION

The brackish upper zone that exists off the Fraser River estuary generally occurs within the upper 5 metres (m) of water. Its presence, at least during the freshet period (late Spring through early Summer) when the Fraser River discharge is high, can be visually detected because of the large amount of light silt it carries. At times the upper zone may be sufficiently thin that the stirring by a passing ship through it permits the deeper clear water to be seen.

When the waters of the central Strait of Georgia are observed from the air, the Fraser River water is easily recognizable by its milky brown appearance against the background of green, darker sea water. In the black and white photographs, the brackish Fraser River water with its variable amounts of silt exhibits various tones of grey; the lighter the tone, the fresher the water and vice versa.

Because of this feature it is possible to interpret the gradual degradation of the grey tone as an indication of the dispersion of silt, and therefore, of the fresh water in the sea. In other words, it is an indication of the increase in the salinity of the source water as it enters the sea. The process is analogous to the dispersion of a solution of dye and fresh water when released into the sea water. The examination of the sequence of aerial photographs thus permits the tracking of the trajectory of the source water (Fraser River water) as it enters the Strait.

INTERPRETATION OF SURFACE WATER FLOW FROM AERIAL PHOTOGRAPHS

Due to the maintenance of the longitudinal pressure head at the river mouth and to the inertia of the river flow, an outflowing tongue of fresh or brackish water is evident at the river mouths. When the river discharge is high, and particularly during the ebbing tide, the outflow at the river mouth is so large that a well-defined, jet-like feature is present. Off the main South Arm (hereafter called Main Arm) of the Fraser River, the flow is so strong that the jet maintains its identity for a considerable distance, at times for several miles. An average speed as large as 5 knots has been observed during its excursion from the mouth of the river to mid-Strait. (Giovando and Tabata, 1970). Lesser, tongue-like plumes appear also at the mouths of the smaller North Arm and Middle Arm. Where such jets or plumes occur, the orientation of their

axes and their gradual darkening of tone can be used to interpret the current direction. These are indicated on the accompanying figures by bold continuous arrows.

At times such a jet-like feature is absent and in its place one notes a cloud of water "accumulating" off the river mouth. In such cases it is likely that the flow within the cloud is radial; that is, the water is spreading in all outward directions from the source due to the occurrence of a pressure head at the mouth. In this case the presumed flow would be indicated by continuous arrows.

At the convergence line between two water masses, one indicated, say, by the silty fresh water and the other by the darker sea water, it is possible to have relative flow; in fact, such observations have been made in the vicinity of the mouth of North Arm (Tabata, Giovando and Devlin, 1971). Where such horizontal shear is likely, the presumed flow is indicated by broken arrows in the accompanying figures. It is also possible that at the convergence one of the water masses may be lighter than the other resulting in the over-riding of the lighter fresh water over the denser seawater. However, it is difficult to determine this from aerial photographs except perhaps at the advancing edge of the plume.

In the discussion to follow, the general features of the results will be presented first, followed by a more detailed description of the water movement.

SURVEY OF 1 JUNE 1950

At this time more than one half of the area (bounded approximately by Point Atkinson-Gabriola Island to the north, Point Roberts - Mayne Island to the south, eastern shores of Gulf Islands to the west and mainland shores to the east) was covered with the silty Fraser River water.

It was generally confined to the eastern side of the Strait during the ebb but its extent doubled during the flood. The plumes originating at the mouth of each Arm, namely the Main Arm, the Middle Arm and the North Arm, were all recognizable in the photographs, the one off the Main Arm, of course, being most prominent. The plume off the North Arm was clearly evident during all stages of the tide but that off the Middle Arm was less well defined and was evident only at certain stages of the tide. Clearer, more saline water, occurred off Valdes Island during the ebb. This water probably has a salinity of about 25 °/oo as inferred from observations at Entrance Island, (Pacific Oceanography Group, 1951) located about 7 miles northwest of Thrasher Rock. Clearer water also occurred at an area midway between Valdes Island and Lulu Island.

1. Initial Stage of Large Ebb (Fig.4).

The main plume originating at the Main Arm was restricted to the region south of the Sand Heads - Porlier Pass line with an indication that it was spreading toward the shores of Galiano Island. At the mouth of North Arm there was evidence of a flow to the northwest in the direction of Bowen Island and some flow to the south, as well as into Burrard Inlet. The flow from the Middle Arm was directed to the north and appears to retain its identity even within the vicinity of the mouth of North Arm (Fig. 5). The fresh water in Howe Sound (Fig. 6) is likely a combination of North and Middle Arm outflow which has moved northward into the Sound. The most saline water (clearest water in the area) occurred along the shores of Valdes Island and northern part of Galiano Island.

2. Halfway through Large Ebb (Fig. 7).

During this period, a more distinct cloud of fresh water appeared off the Main Arm. This feature is presumably due to the fresh water that had been stored in the river mouth during the flood that was subsequently released with the lowering of sea level in the Strait. The jet-like plume that occurred backed sharply to the south. This southerly set could have been caused by the ebb flow in the Strait, although the fresh north-westerly wind that was blowing at the time (Table 1a) could have influenced it somewhat. The area covered with fresh water in the southern part increased from that of the previous flight. There was little change in the circulation pattern off the North Arm from that of the previous flight except that the boundary marking the salt water - fresh water convergence was more clearly defined (Fig. 8) than previously (cf. Fig. 5). The water from the Middle Arm was still discernable although its plume was somewhat obscured. As during the previous period, clearer water again occurred off the shores of Gabriola and Galiano Islands.

3. Final Stage of Large Ebb (Fig. 9)

The fresh water accumulating at the mouth of the Main Arm appeared well marked. It covered an area to the south of Sand Heads with the bulk of the water flowing to southwest. There was evidence of some fresh water flowing southward past Point Roberts from its probable origin at Canoe Pass. Off the North Arm and Middle Arm the flow pattern remained essentially similar to that observed during the previous stages of the tide, although

the flow off the Middle Arm was more distinct (Fig. 10). The area of clearer sea water was almost as large as during the previous tide. There was some evidence of fresh water lying south and southwest of Bowen Island; however, it is difficult to establish where it originated. It could have been due to flow from the North and Middle Arms during previous tides, or from the Main Arm as it appeared to have been separated from the bulk of water originating at the North and Middle Arms by an area of clearer brackish water.

4. <u>End of Large Ebb - Lower Low Water</u> (Fig. 11)

The plume from the Main Arm showed expansion to the west as well as to the southwest in comparison to the previous stage of the tide (Fig. 9) when it showed expansion to the southwest only. The boundary between the plume and the adjacent sea water appeared most marked in the series of photographs taken during this flight, as compared to those of the previous flights. The fresh water flowing southward past Point Roberts was also marked as can be seen from Fig. 12. Off the North Arm there appeared to be more flow directed into Burrard Inlet and toward Bowen Island (Fig. 13). Off the Middle Arm the bulk of the water flowed to the north, some merging with the plume from the North Arm (Fig. 14). This feature was observed again on 11 June 1969 during a similar stage of the tide (Tabata, Giovando and Devlin, 1971). There was some evidence to imply that some of this Middle Arm water also flowed southward. The character of the plumes from the three Arms can be clearly seen in Fig. 15.

5. Initial Stage of Large Flood (Fig. 16)

A noticeable change occurred in the behaviour of the main plume; a distinct veering took place and the plume changed its course to northeast, probably reacting to the flood tide. Apart from the intensification of the flow of water into Burrard Inlet the circulation pattern off the North Arm remained similar to that observed during the previous stages of the tide. As can be seen from Fig. 17, a sizeable area of the central Strait was covered with the Fraser River water. The area occupied by the clearer sea water along the eastern shores of Galiano and Valdes Islands appeared to have diminished somewhat by the beginning of flood.

6. Halfway through Large Flood (Fig. 18)

By this stage of the tide, more than half of the area was covered with water originating from the Fraser River. The main plume had increased its veer and its area in all directions. Off the North and Middle Arms, little change occurred in the flow pattern evident during the previous stages of the tide.

7. Final Stage of Large Flood (Fig. 19)

Due to excess reflection present in the photographs taken during this flight the photographs are not of sufficient quality to allow any detailed examination. However, it appears that the extent of the fresh water in the area was similar to that observed during the previous stage of the tide. The fresh water lying east of Galiano Island and Valdes Island had moved westward with part of it lying close to Porlier Pass. Clearer sea water appeared to have flowed northward past Point Roberts.

Distribution of Surface Salinity (29 and 31 May 1950) (Fig. 20)

Oceanographic observations were made along the eastern half of the central Strait during the day of the aerial survey and on a few days preceding it. The lack of synopticity and the low density of samples do not permit a detailed comparison of oceanographic features interpreted from these observations with those from aerial photographs. However, comparison showed that there is a resemblance in the general oceanographic features indicated by each set of observations. The following features were present in the oceanographic data and were consistent with those obtained from aerial survey:

a. relatively saline water occurred along the north shore of Burrard Inlet;

b. relatively fresh water was present over the bulk of Burrard Inlet;

c. low salinity water off the North Arm and the Middle Arm was present but seaborne observations showed them to be isolated "clouds";

d. low salinity water off the Main Arm also appeared as an isolated "cloud" in seaborne observations while it was continuous in the observations made from aerial survey;

e. relatively unmixed sea water (salinity of about $^{o}/oo$) appeared approximately 5 miles from the low tide boundary of Sturgeon Bank.

Distribution of Internal Waves during 1 June 1950.

Internal waves are waves that occur below the water surface between layers of different density or within layers where vertical density gradients are present. Their presence in the sea, when observed from ships or aircraft, is frequently indicated by the occurrence of alternate bands of ruffled and smooth water or of slicks on the sea surface. In the central Strait of Georgia

these bands sometimes appear as strips of greenish-yellow filaments. (In the accompanying figures these waves are shown by a series of wavy lines representing wave crests).

Shand (1955) was the first to remark on the presence of internal waves in the Strait of Georgia. Utilizing the aerial photographs obtained during the 1950 Survey and those taken subsequently, he was able to describe the main features of these waves. In the present report it will be sufficient to report their presence at the various stages of the tide and to discuss their possible influence upon the surface circulation.

Internal waves appeared initially in a relatively small area off Point Roberts a few hours before Lower Low Water (Fig. 9). At Lower Low Water they occurred over a wider area, between Point Roberts and Mayne Island and off Active Pass (Fig. 11). During the initial stage of the Large Flood they were distributed over a much greater area during the previous stages of the tide (Fig. 16). Not only were they present in a large area between Point Roberts and Galiano Island, but also occurred between Gabriola Island and Point Grey. During the next stage of the tide (halfway through the Large Flood) the location of these waves in both the southern and northern areas was displaced about 5 miles to the north of the position occupied during the previous stage (Fig. 18). In addition to these, another band of waves occurred off Sturgeon Bank just north of Sand Heads. During the final stage of the Large Flood they occurred only in the area between Point Roberts and Galiano Island.

SURVEY OF 9 AND 10 JUNE 1950

Increased cloudiness during 9 June precluded the completion of the survey scheduled for that day; nonetheless, it was possible to complete the 7 flights on the following day which was a period of small tides. A 20% increase in the Fraser River discharge occurred during the interval between the previous survey on 1 June and the present one.

The most conspicuous features of the distribution of silty fresh water in the area during this period were the occurrence of a well-developed jet off the Main Arm and the presence of a "clockwise loop" in the central part of the area. Fresh water, or very low salinity water, occured along both the eastern and western sides of the area with a patch of clearer seawater in between. The general location of the "loop" remained relatively unchanged during the entire day of observations.

1. Halfway through Large Ebb (Fig. 21)

During this stage of the tide, it was evident that the plume originating at the mouth of the Main Arm had formed a well-defined jet whose axis was oriented parallel to Steveston Jetty, with the advancing edge of the jet lying halfway between Sand Head and Porlier Pass. Although not directly connected with this jet, the fresh water mass that originated in the Main Arm and lying to the south of the jet appeared to extend to the eastern shores of Galiano Island. This water mass then seemed to continue north-westward and veered in the vicinity of Thrasher Rock; it then veered further to form a"clockwise loop" so that the "tongue" of the plume was directed southward. Off the North Arm the circulation pattern was similar to that observed during the previous survey; that is, there was a flow seaward with one branch

flowing into Burrard Inlet, another flowing toward Bowen Island and still another backing to form southerly flowing water. Again, there was evidence of some of the water originating off the Middle Arm flowing north, as well as to the south. Clearer water occurred in the central part of the area.

2. Final Stage of Large Flood (Fig. 22)

The jet-like plume advancing seaward from the Main Arm was again very well-defined and its seaward extent had advanced about 3 miles farther from the position held previously (top right hand corner in Fig. 23). The flow off the North Arm was not very different from that of the previous stage of the tide in which there was the usual seaward flow with some entering Burrard Inlet and the other directed to southwest. Off the Middle Arm and particularly from the area of the Iona Channel (now closed off but formerly located between Iona Island and Sea Island) there was evidence of northerly flow. As evident from Fig. 23, the fresh water off Galiano Island appeared to have continued northward, hugging the shores of northern Galiano Island and Valdes Island. The veering that occurred off Thrasher Rock can be seen readily in Fig. 24. The continuation of this water toward the centre of the area can also be noted in the latter figure. The northernmost extension of this loop penetrated as far as off Collingwood Channel, just west of Bowen Island as can be noted in Fig. 25. There is also some evidence of a small jet-like plume emanating from Canoe Pass to the south of the Main Arm.

3. Initial Stage of Large Flood (Fig. 26)

The main feature of the flow emerging from the Main Arm was the presence of a jet which was almost as pronounced as it was during the previous stage of the tide (cf. Fig. 21). Its forward extremety had reached to within 2 miles of Porlier Pass. This and the well-defined feature of the jet can readily be seen in Fig. 27. The "fresh" water hugging the shores of Galiano and Valdes Island now appeared to be narrower than it had been previously. The clockwise loop that appeared during the two previous stages of the tide was still present. At the mouth of the North Arm the pattern of flow was much the same as it was in the past. A back eddy appeared to be present in Burrard Inlet, just off Point Grey (Fig. 28). The northward flow off the Middle Arm was clearly evident by its jet-like appearance (Fig. 28). The plume associated with Canoe Pass occurred again as a narrow jet, as was noted in the previous stage of the tide.

4. Halfway through Large Flood (Fig. 29)

The jet emanating from the Main Arm continued to be well defined and it appeared that the advancing edge almost reached the "fresh" water associated with the loop. The advancing tongue of the loop showed a more definite tendency to flow southward. In the previous stages of the tide it was not particularly easy to see whether or not the water associated with this advancing tongue was part of the fresh water originating in the North Arm. During this stage of the tide it was clearly evident that the water of the loop was indeed separated from that associated with the North Arm and therefore was unlikely to be connected with it.

The influence of the loop as far as Collingwood Channel is evident from Fig. 30.

5. Final Stage of Large Flood (Fig. 31)

The main plume appeared basically similar to that observed earlier except that the advancing edge now seemed to have merged with the "fresh" water lying off Porlier Pass. Nonetheless, the demarcation line separating these two sources of relatively fresh water was present, as can be seen in Fig. 32. As in the past, the clockwise loop was present. No particular change in the flow pattern off the North and Middle Arms was discernable from that of the previous stages of the tide. There was a narrow band of fresh water off Canoe Pass which is attributed to the flow from there.

6. Initial Stage of Small Ebb (Lower High Water) (Fig. 33)

Although the photographic coverage of the area during this stage of the tide was incomplete, it was still possible to see most of the features of the circulation in the area. The well defined main plume, the clockwise loop and the flow off the North Arm were basically similar to those observed during the previous stages of the tide.

It is to be noted here that on 4 June 1968, oblique photographs of the waters lying off the eastern shores of Galiano and Valdes Islands were taken. The time of photography coincided with that of a small ebbing tide (Fig. 2) during the presence of light northwest winds (Table 1d) and when the Fraser River discharge was about 300,000 ft^3/sec (Fig. 3). Although the river discharge was about 50% greater than it was at the corresponding period in 1950

the conditions of the tide and winds were similar to those encountered in 1950 (cf. Fig. 2b, 2d and Tables 1b, 1d). At this time a strip of "fresh" water (characterized by its light colour), which resembled a part of the loop observed during 1950, was present (Fig. 34). This indicates that the "fresh" water observed at the same location during 1950 was not an isolated event.

7. Halfway through Small Ebb (Fig. 35)

Only vertical photographs were available for this flight and hence the coverage of the area was restricted. The circulation pattern off the North and Middle Arms, as deduced from the present series of photographs, indicated that it was the same as during the previous stage of the tide.

Flights of 9 June 1950 (Fig. 36 and 37)

As mentioned earlier, only 2 flights were made on the 9th of June 1950. The first set of photographs were taken during the final stage of large ebb and therefore correspond to that obtained during the second flight on the 10th of June (Fig. 22). The second set was obtained during the initial stage of the large flood and corresponds to that obtained during the third flight on the 10th of June (Fig. 26). A comparison of observations made on the similar stages of the tide on the two days, indicated that most of the features represented on the 9th of June were reproduced on the 10th of June. The main jet-like plume off the Main Arm, the clockwise loop, the flow off the North Arm all are present in the two sets. Perhaps the only difference lies in the fact that the area occupied by the fresh water to the south of Bowen Island appeared to have been greater on the 9th than on the 10th of June.

Distribution of Surface Salinity (13 and 14 June 1950) (Fig. 38)

Oceanographic observations of surface water along the eastern part of the Strait were made during the 13th and 14th 1f June some few days after the time of the aerial survey. These observations were made within $9\frac{1}{2}$ hours on each day and therefore possessed slightly more synopticity than those taken during the 29th and 31st of May which were taken over a period of 2 days on each set. Because of the time scales involved, it is difficult to compare aerial and seaborne observations that were separated by several days. However, the surface features represented by aerial photography did resemble those based on seaborne measurements. For example, the shipborne observations showed the increased amount of fresh water in the area during this period and recorded plumes off all the major arms of the river. A narrow tongue of fresh water can be seen off the Main Arm off Sand Heads (Fig. 38a) and is likely to be associated with the jet mentioned earlier.

Distribution of Internal Waves during 10 June 1950

Internal waves were confined to the southern area of the Strait during this survey. They first appeared in a relatively small area off Point Roberts (Fig. 21) during the time of "Half-way through the Large Ebb", and during subsequent stages of the tide, occurred over a wider area than initially. However they were restricted to the area between Point Roberts and Galiano Island (Fig. 22, 26, 29, 31 and 33).

MINI-SURVEY OF 5 JUNE 1948 (Fig. 39)

The latter part of May and the early part of June 1948 were characterized by a very large Fraser River discharge (Fig. 3) when flooding occurred in the Fraser River valley. It was during this period that a pair of oblique photographs were taken over the central Strait of Georgia. As might be expected, a substantially large area of the central Strait was covered with Fraser River water. As is evident in Fig. 39 and 40, the entire eastern part of the central Strait from the area of Point Roberts to Sechelt along the eastern shores to Sand Heads and down to Saturna Island was influenced directly by the Fraser River. Although the location of the main plume was not adequately covered by the aerial photographs it is possible to note the smaller plumes off the North and Middle Arms (Fig. 39) and off Canoe Pass (Fig. 40).

SUMMARY OF RESULTS AND DISCUSSION

A set of vertical and oblique aerial photographs of the surface waters of the central Strait of Georgia, obtained about 2 decades ago, has been utilized to interpret the movement of Fraser River-influenced waters. The interpretation of surface water movement from vertical photographs can be made with relative ease. That from oblique photographs, however, presents some problems due to the perspective distortion and subsequent difficulty of interpreting surface events that lie more than several miles away from the flight track. Further, reflection from distant clouds may give misleading surface images which need to be taken into consideration when interpretation of oblique photographs is made.

A description of the circulation pattern of the surface waters is made, using silt in the water as a natural tracer. The fresh-water plumes, recognizable because of their silt content, emanating from the mouth of the three arms of the Fraser River -- Main Arm, Middle Arm and North Arm -- can all be distinguished. The plume off the Main Arm is most easily depicted because of the large volume of water involved. At times this plume is well developed and appears as a well-defined jet, suggesting the importance of the inertial and pressure forces. Distinct features of this jet can be traced to Porlier Pass, about 12 miles from the source, and further.

One of the more prominent features depicted in the series of photographs is a "clockwise loop" whose water appears to have originated in the Main Arm, crossed the Strait to its western side, moved northwestward along the eastern shores of Galiano and Valdes Island, veered to the northeast, extending as far as Collingwood Channel just west of Bowen Island, then flowed southward. The fact that such a loop can occur for

one half day and that it shows signs of existing for even longer periods is of particular interest because of its implications about the maintenance of the dynamic balance in such an estuarine circulation. In a theoretical attempt to explain estuarine circulation Takano (1955) considered a balance of pressure gradient, Coriolis force, vertical and lateral mixing, while ignoring inertial and other effects such as tides and suggested that a slow-moving plume in the northern hemisphere should spread with a deflection to the right of the direction of the flow. Qualitatively there is a deflection of the Fraser River plume to the right, but the fact that it remains in a relatively narrow band implies that lateral mixing is small (at least, in the present case) and that inertial and other effects are important also. During the ebb the entrant direction of the main plume is maintained which suggests the balance of Coriolis and ebb-tidal forces during this period (Ebb currents in the Strait should be flowing southeastward). If the loop is to occur for more than one day as the data suggest, it must derive some energy to maintain the flow and must have an adequate supply of fresh water to maintain its identity, otherwise tidal mixing alone probably would be sufficient to destroy its unique distribution. It is suggested that its occurrence is maintained by the daily "push" resulting from the jet from the Main Arm merging with the already-present fresh water lying along the western side of the Strait.

As has been described in previous studies (Fjarlie, 1950), the plume from the North Arm is directed into Burrard Inlet as well as seaward. Even during the ebb, some flow, though apparently weaker than during the flood, appears to be directed into Burrard Inlet. Part of the explanation for the northward flowing current may be due to the deflection caused by Coriolis force; however, it is more likely that the observed

circulation pattern at the mouth of the North Arm is attributable to the build-up of pressure gradient here due to the accumulation of fresh water at the mouth that generates radial flow, part of which could be northward-moving flow.

It has been shown here and in other studies (Tabata, Giovando and Devlin, 1971) that off the Iona Jetty the surface water within a mile or so from the low-tide boundary moves northward even during the ebb tide. The reason for the occurrence for this flow is not readily explicable. It does not appear to be due to the pressure gradient at the mouth of the Middle Arm alone.

The importance of pressure gradients in the area has not been delt with in detail due to lack of suitable data. Where such an effect has been examined elsewhere, it has been found to have important influence on the circulation. Off the Mississippi River, for example, it has been estimated that the sea level decreases by 1 foot per 6 miles seaward from the mouth of the river (Bates, 1953). If the Fraser River is being discharged at a rate of 200,000 ft^3/sec, at the mouth, this volume will be sufficient to raise a water column of an area comparable to the eastern half of the Strait (Point Grey to the north and Point Roberts to the south) by $3\frac{1}{2}$ ft per day. In practice, such an accumulation of water is unlikely to occur since the fresh water is continuously pouring into the sea and also since there is a tendancy for an adjustment of water masses in the deeper layers which decreases the potential energy of the water column. However, such a rate ($3\frac{1}{2}$ ft per day) does indicate the contribution of the fresh water discharge in creating an horizontal pressure gradient that may be responsible for some of the flows depicted.

Internal waves were present from the time of the final stage of

the ebb through the flood. Their occurrence was most common in the area between Point Roberts and Mayne Island and was most prevalent during the large tides. They appear to progress not only along the axis of the Strait but also across it. An examination of internal waves in the southern area, in recent years, has shown that they possess periods between 2 and 3 minutes, wave lengths varying from 50 to 4000 ft and celerity exceeding ½ knot (Hughes, 1969). The velocities associated with these waves are comparable to those of tidal currents and therefore are likely to distort the general circulation pattern in the area.

The gross feature of the distribution of silt is correlated with that of salinity, at least in the eastern half of the Strait. The aerial photographs show considerable details of the distribution of silt and therefore of the fresh water. A comparison of the details interpreted from photographs and those made from seaborne observations is not possible. The major difficulty is due to the lack of synopticity and the low level of sampling in the seaborne observations. The assessment of the deduced surface circulation from aerial photographs is hampered by lack of direct current measurements for the verification of the interpreted flow. In future surveys of this sort it is essential that this aspect of observations be considered as the deduced flows would have much more significance had they been supported by seaborne measurements. Further, a rapid survey made by towed instruments from high speed vessels during the aerial survey would provide appreciable material to aid the interpretations of results.

ACKNOWLEDGEMENTS

Thanks are to Mrs. Velma Nadon and Mrs. Joyce Fagan for the assistance in preparing the working and the final drawings. Appreciation is due to Dr. R.E. Thomson for his review of the manuscript.

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TIME → (hour ending) DATE ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
(a) 31 May 1950	NE 3	N 4	NE 3	E 3	E 3	E 3	calm	NW 1	W 4	W 9	W 8	W 7	W 6	W 7	W 9	W 6	SW 7	W 4	W 3	calm	SE 2	E 3	E 6	E 5
1 June 1950	SE ?	SE 4	SE 5	NE 4	NW 4	NW 14	NW 16	NW 14	NW 18	NW 17	NW 17	NW 16	NW 13	NW 12	NW 13	NW 12	NW 13	NW 15	NW 13	NW 15	NW 10	NW 5	W 3	NW 4
(b) 8 June 1950	SE 10	SE 10	SE 10	SE 8	SE 6	SE 10	SE 11	SE 10	SE 10	SE 10	SE 9	SE 9	SE 10	SE 8	SE 6	S 6	S 4	S 4	S 3	S 3	SE 3	E 3	E 3	E 3
9 June 1950	NE 3	E 3	E 3	E 1	calm	calm	calm	W 4	W 6	W 9	W 10	W 9	NW 12	W 12	NW 12	NW 12	NW 11	NW 11	NW 10	NW 6	NW 6	NW 4	NW 1	N 3
10 June 1950	NE 1	NE 4	NE 4	NE 3	N 3	W 3	W 9	NW 5	W 12	NW 10	NW 10	NW 10	NW 11	NW 11	NW 11	W 6	W 6	W 6	NW 5	NW 3	NW 1	S 4	E 4	E 6
(c) 4 June 1948	E 4	E 3	E 4	E 6	E 1	E 1	SE 3	SW 3	SW 3	W 7	NW 10	NW 10	NW 8	NW 9	NW 8	W 8	SW 6	S 5	S 5	SE 4	SE 5	SE 6	E 5	E 5
5 June 1948	E 8	E 4	E 2	calm	NE 2	W 1	E 3	E 1	NW 9	NW 10	NW 10	NW 11	NW 9	NW 11	NW 11	NW 11	NW 10	NW 10	NW 7	NW 6	NW 1	SE 3	E 3	NW 3
(d) 3 June 1969	NW 5	E 2	calm	E 1	E 2	E 2	E 3	E 3	E 3	NW 5	NW 9	NW 8	NW 10	NW 10	NW 10	NW 10	NW 10	NW 10	NW 9	NW 9	NW 9	N 8	N 4	calm
4 June 1968	calm	N 1	N 2	calm	SE 1	SE 1	calm	NW 1	NW 4	NW 6	NW 6	NW 6	NW 4	NW 5	W 5	W 5	W 5	W 5	W 4	W 2	W 1	S 2	calm	E 2

Table 1. Prevailing wind directions with total number of nautical miles for each hour (hour ending) at Vancouver International Airport.

a. For the period 31 May - 1 June 1950

b. For the period 8 - 10 June 1950

c. For the period 4 - 5 June 1948

d. For the period 3 - 4 June 1968.

Fig. 1. Chart showing the location of the general area of observations. The hatched area is along the flight track and represents the area covered by vertical photography.

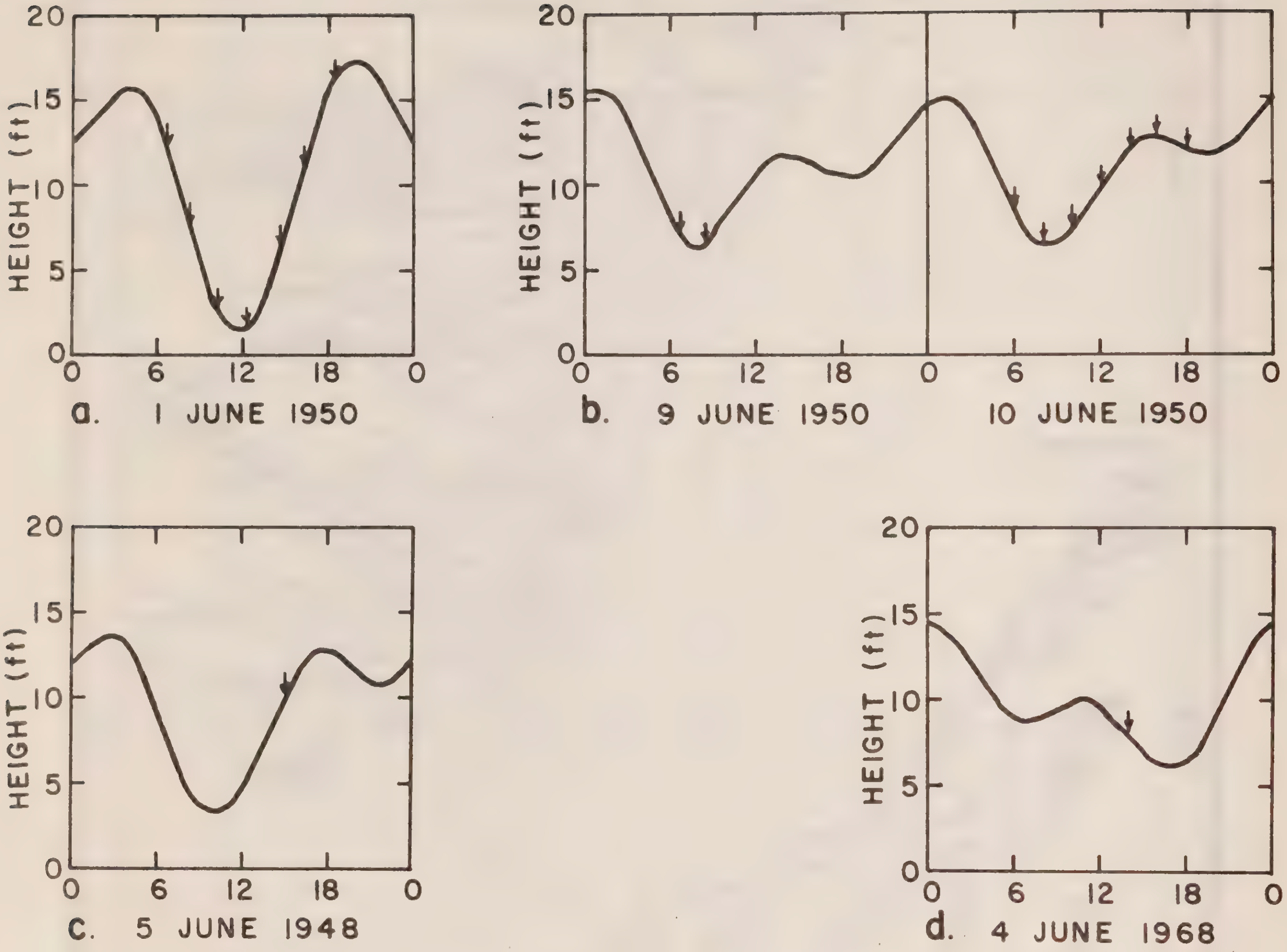

Fig. 2. Tidal heights at Point Atkinson:

a. for the period 1 June 1950
b. for the period 9 - 10 June 1950
c. for the period 5 June 1948
d. for the period 4 June 1968

(arrows denote times of photography)

Note: Tidal heights for 1948 and 1950 have been adjusted by adding 1.3 feet to the published predicted values to conform with current practices.

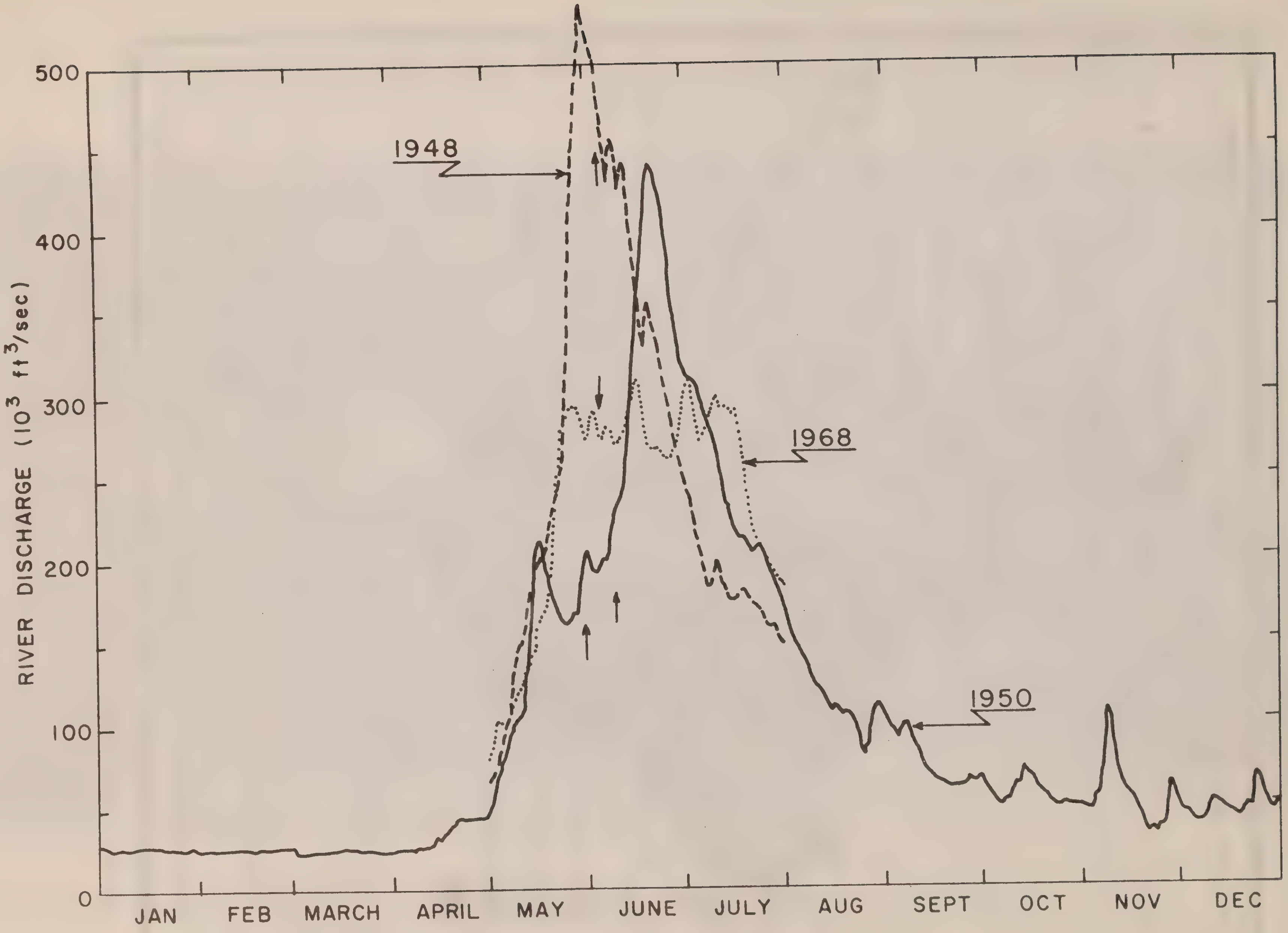

Fig. 3. Fraser River discharge (ft^3/sec.) measured at Hope, B.C.
Vertical arrows indicate dates of photography.
Only portions of data for 1948 and 1968 are shown.

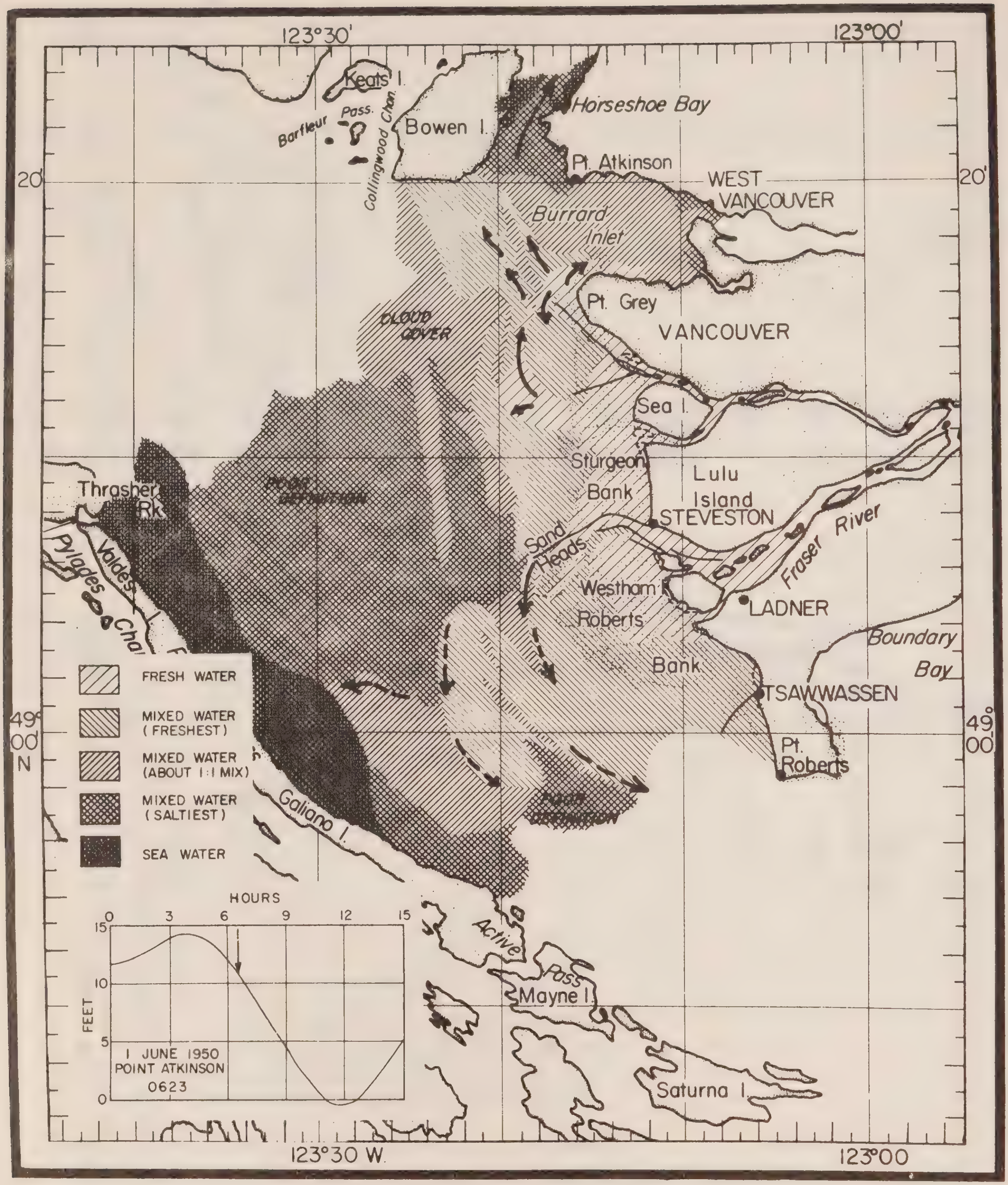

Fig. 4. Distribution of water types in the central Strait of Georgia during the initial stage of large ebb on 1 June 1950, as deduced from a series of vertical and oblique aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with regard to directions than indicated by solid arrows.

Fig. 5. Mosaic of vertical photographs taken during the initial stage of large ebb on 1 June 1950 showing a plume which appears to have originated in the Middle Arm or from Sturgeon Bank. The plume from the North Arm is shown to split into two, one directed to the south and the other to the northeast.

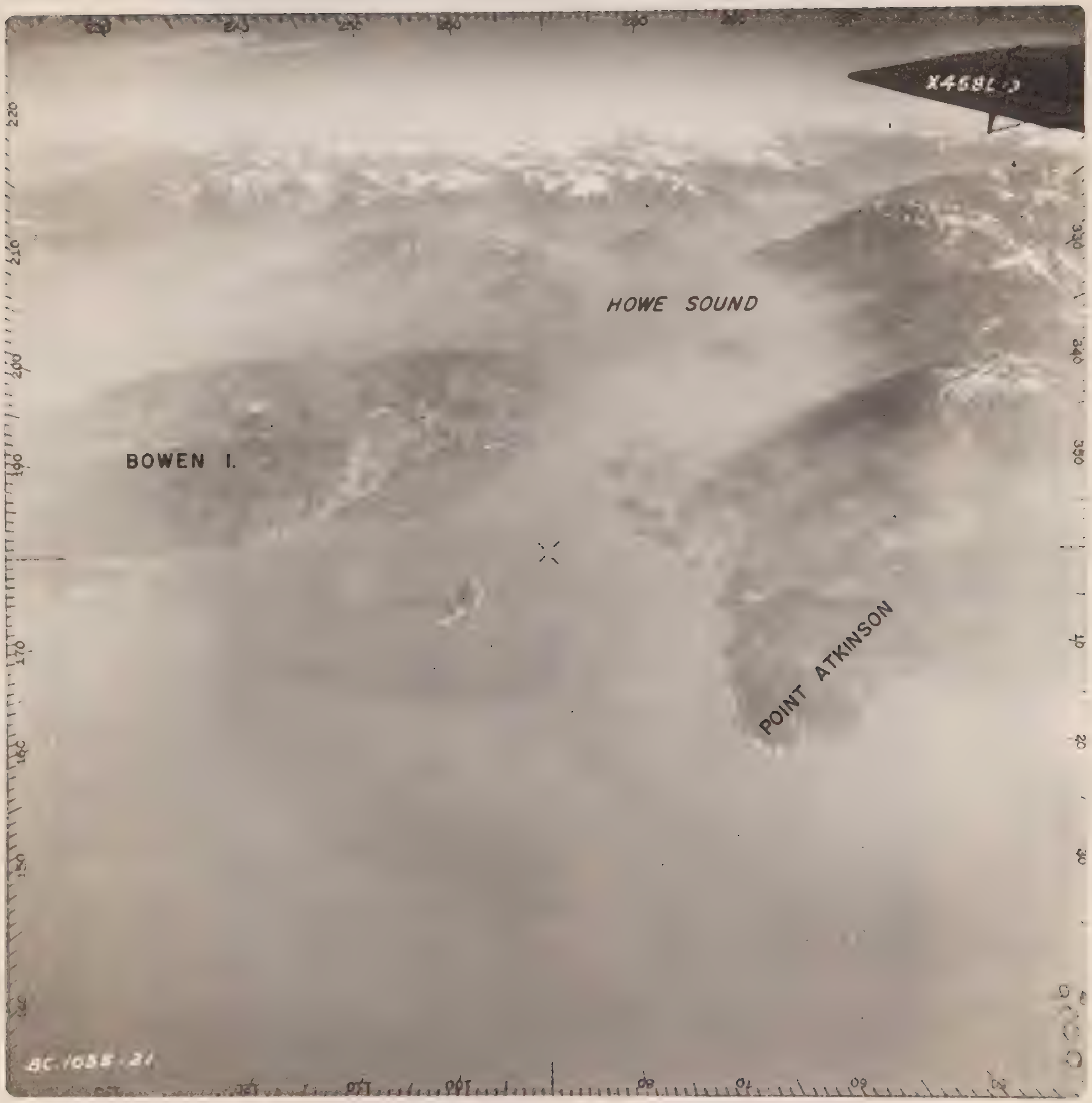

Fig. 6. Oblique photograph taken during the initial stage of large ebb on 1 June 1950 showing brackish water from the south entering Howe Sound.

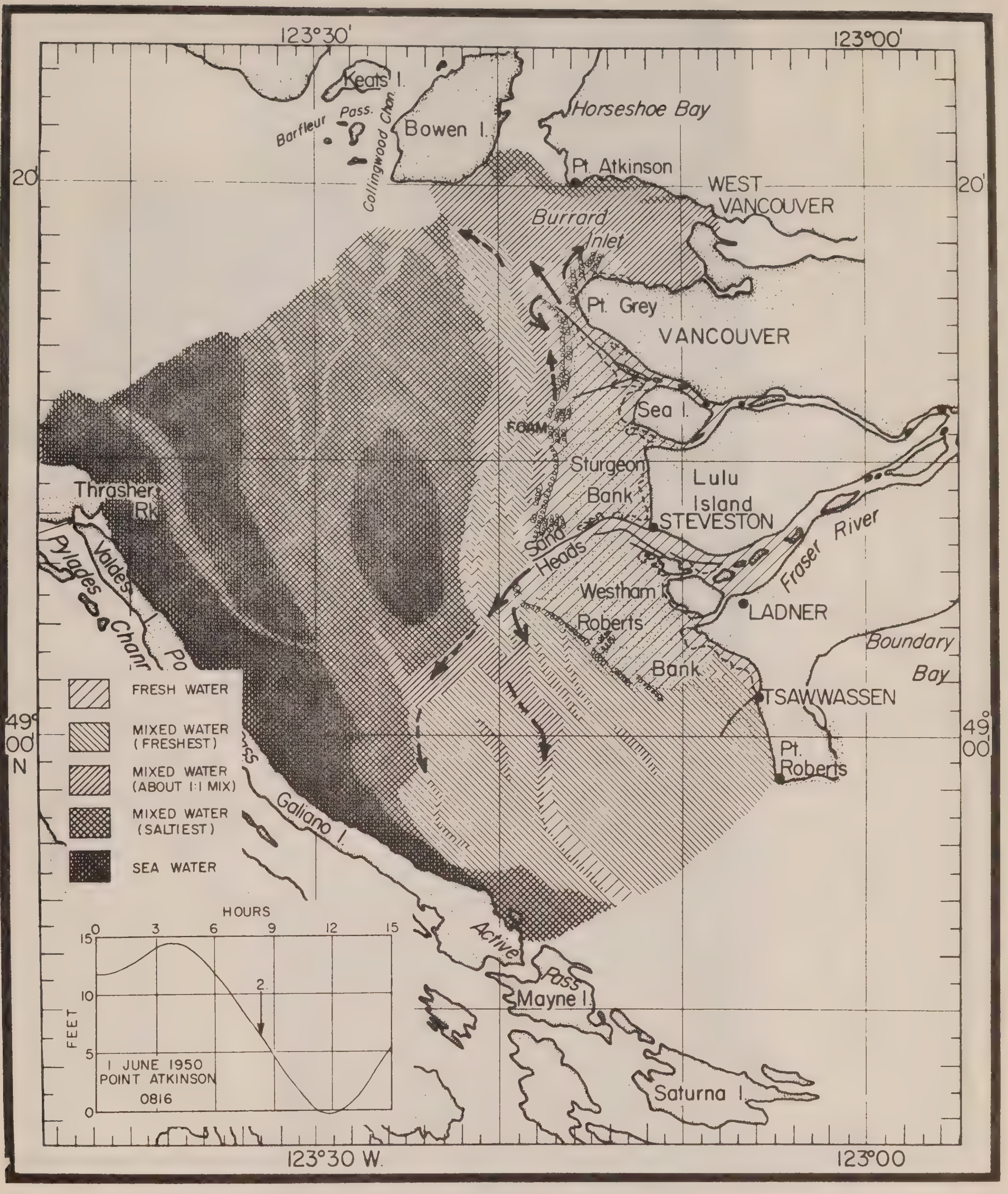

Fig. 7. Distribution of water types in the central Strait of Georgia during halfway along large ebb, on 1 June 1950, as deduced from a series of vertical and oblique photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows.

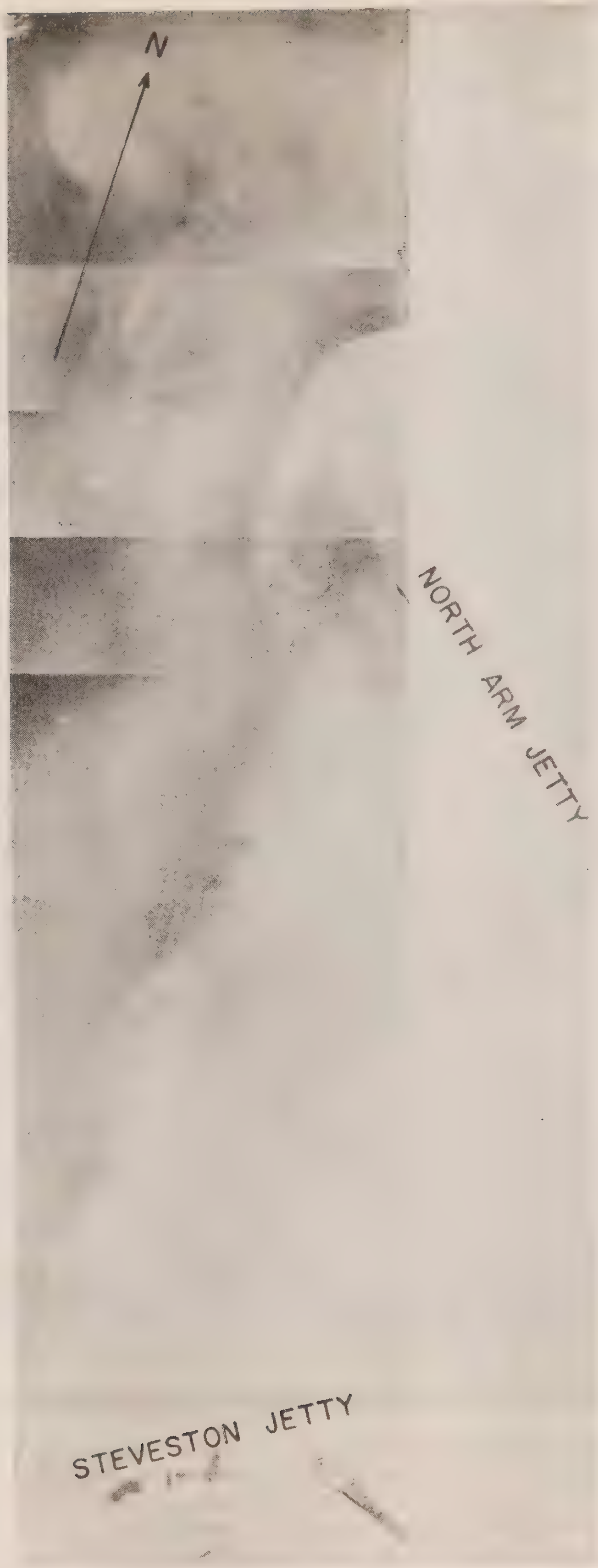

Fig. 8. Mosaic of vertical photographs taken during halfway along large ebb on 1 June 1950 showing the plume that appears to have originated in Middle Arm of Sturgeon Bank. The plume from North Arm shows expansion to seaward as well as to south and northeast.

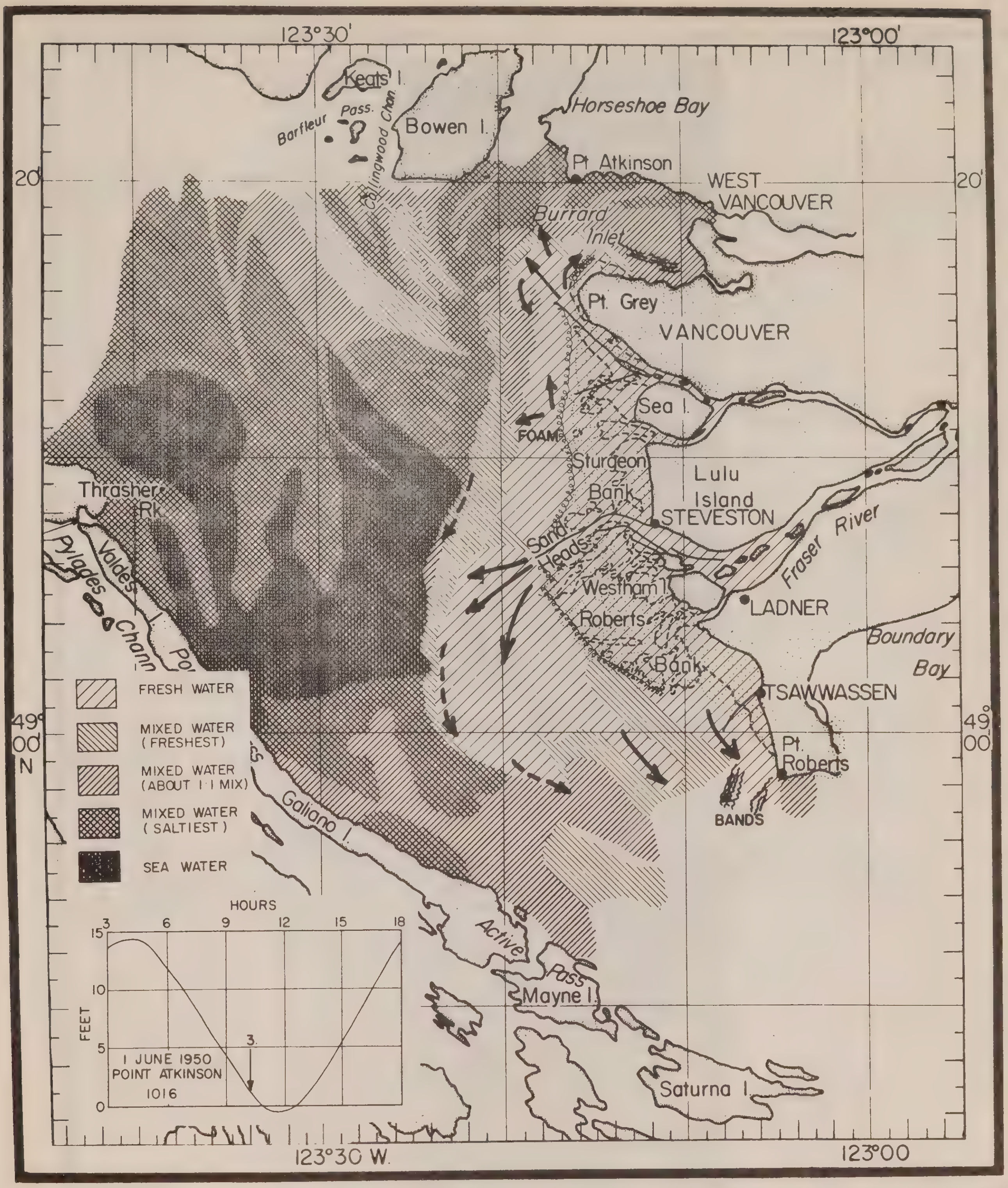

Fig. 9. Distribution of water types in the central Strait of Georgia during the final stage of large ebb on 1 June 1950, as deduced from a series of vertical and oblique aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty than indicated by solid arrows. Bands denote alternated bands of ruffled and smooth water surface indicating the presence of internal waves (lines represent crest of waves).

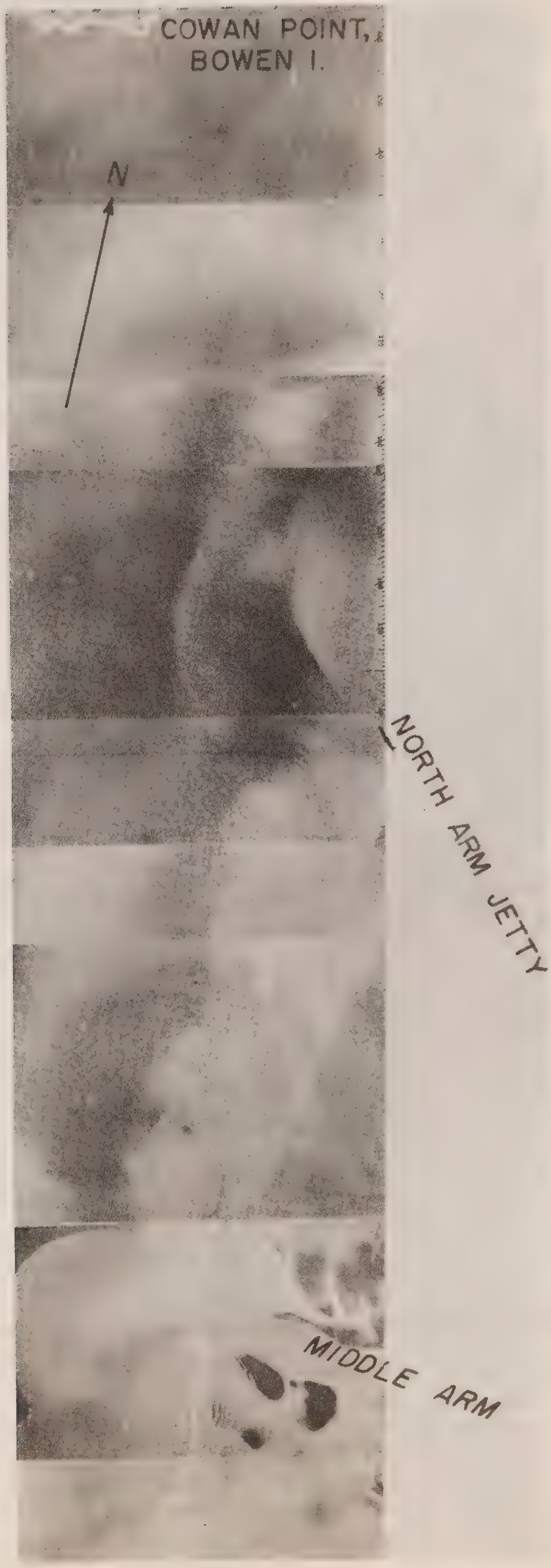

Fig. 10. Mosaic of vertical photographs taken during the final stage of large ebb on 1 June 1950 showing plume originating in Middle Arm and North Arm.

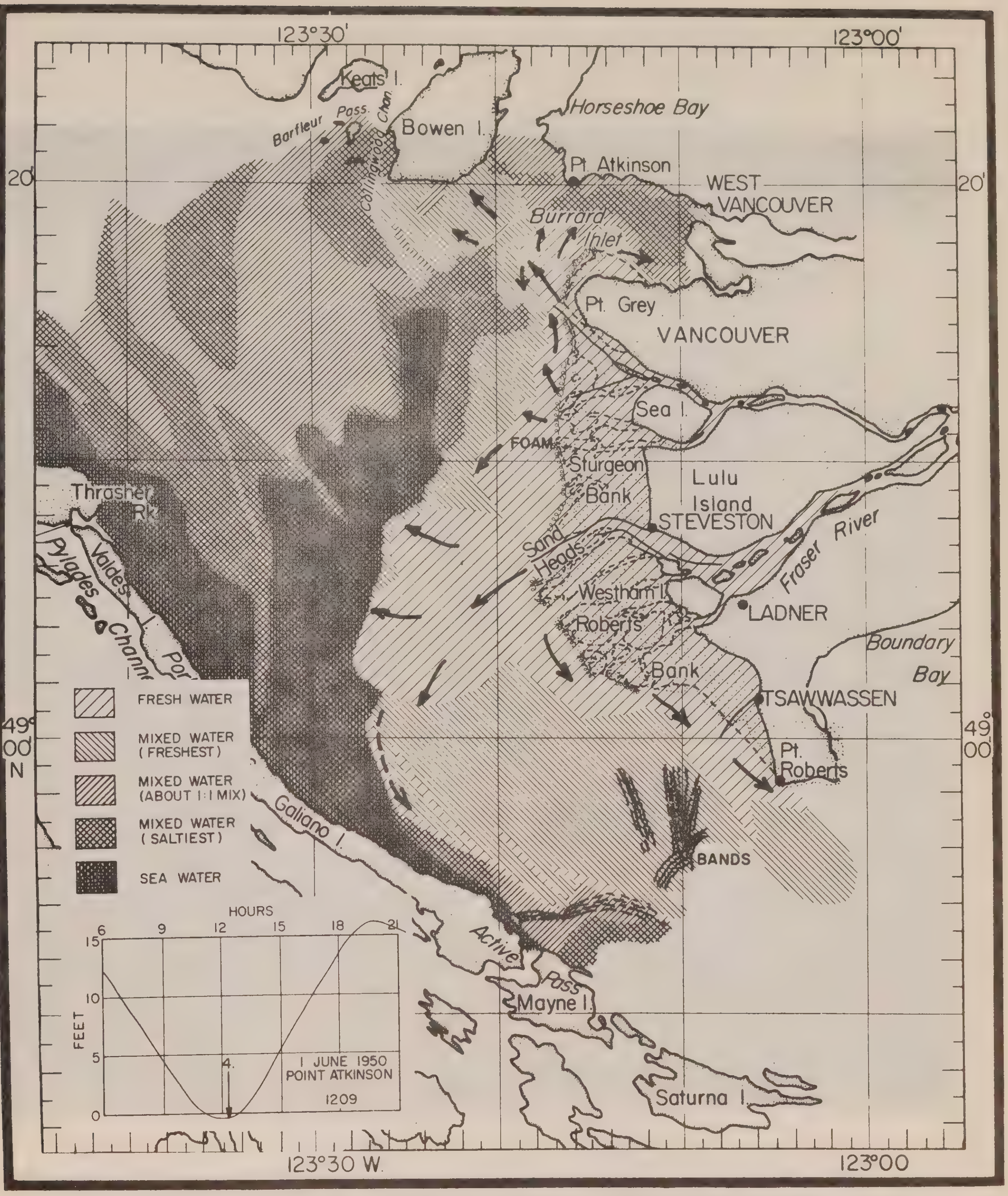

Fig. 11. Distribution of water types in the central Strait of Georgia during end of large ebb (Lower Low Water) on 1 June 1950 as deduced from a series of vertical and oblique aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves (lines represent crest of waves).

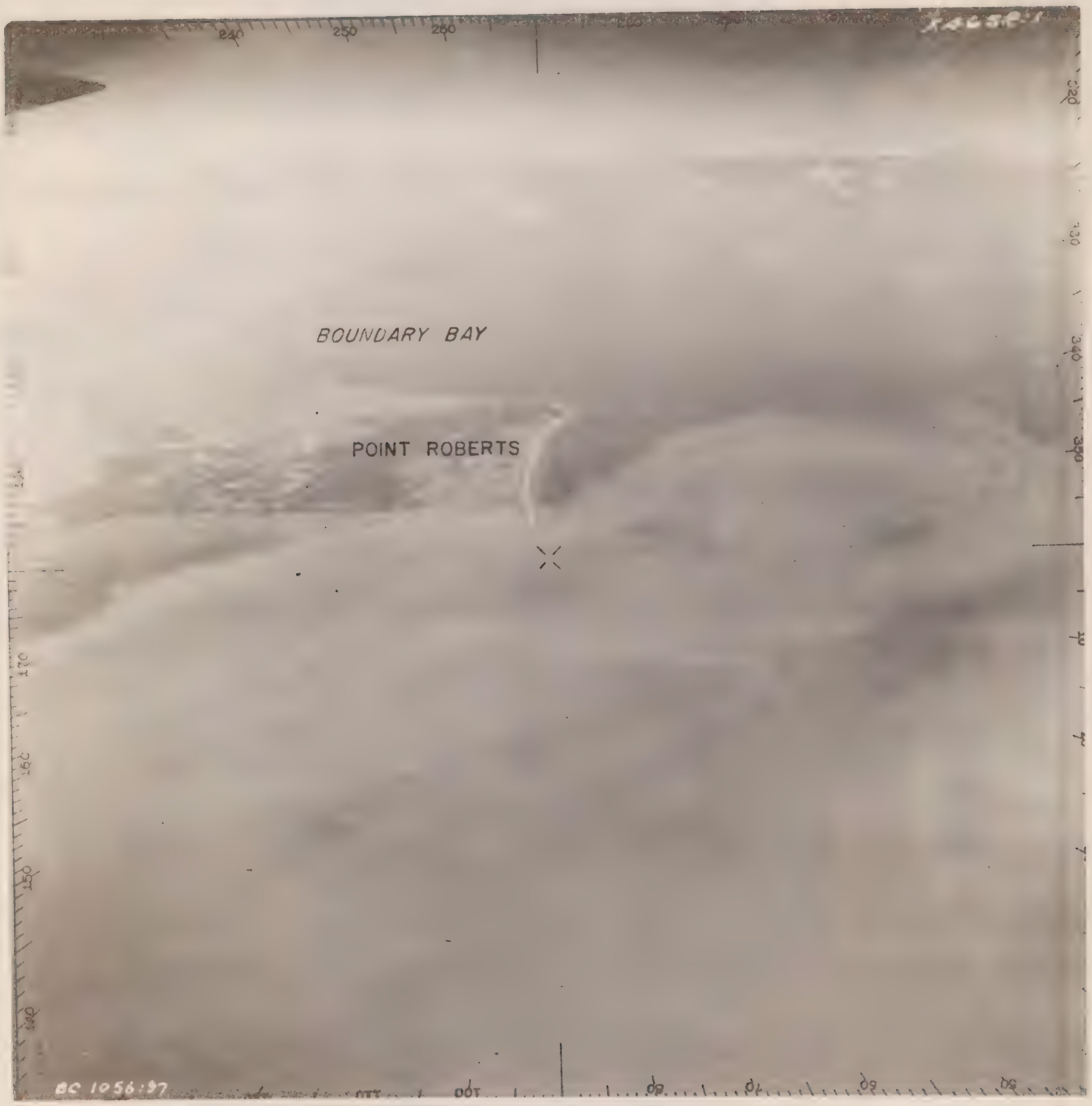

Fig. 12. Oblique photograph taken during end of large ebb 1 June 1950 showing fresh water flowing south past Point Roberts.

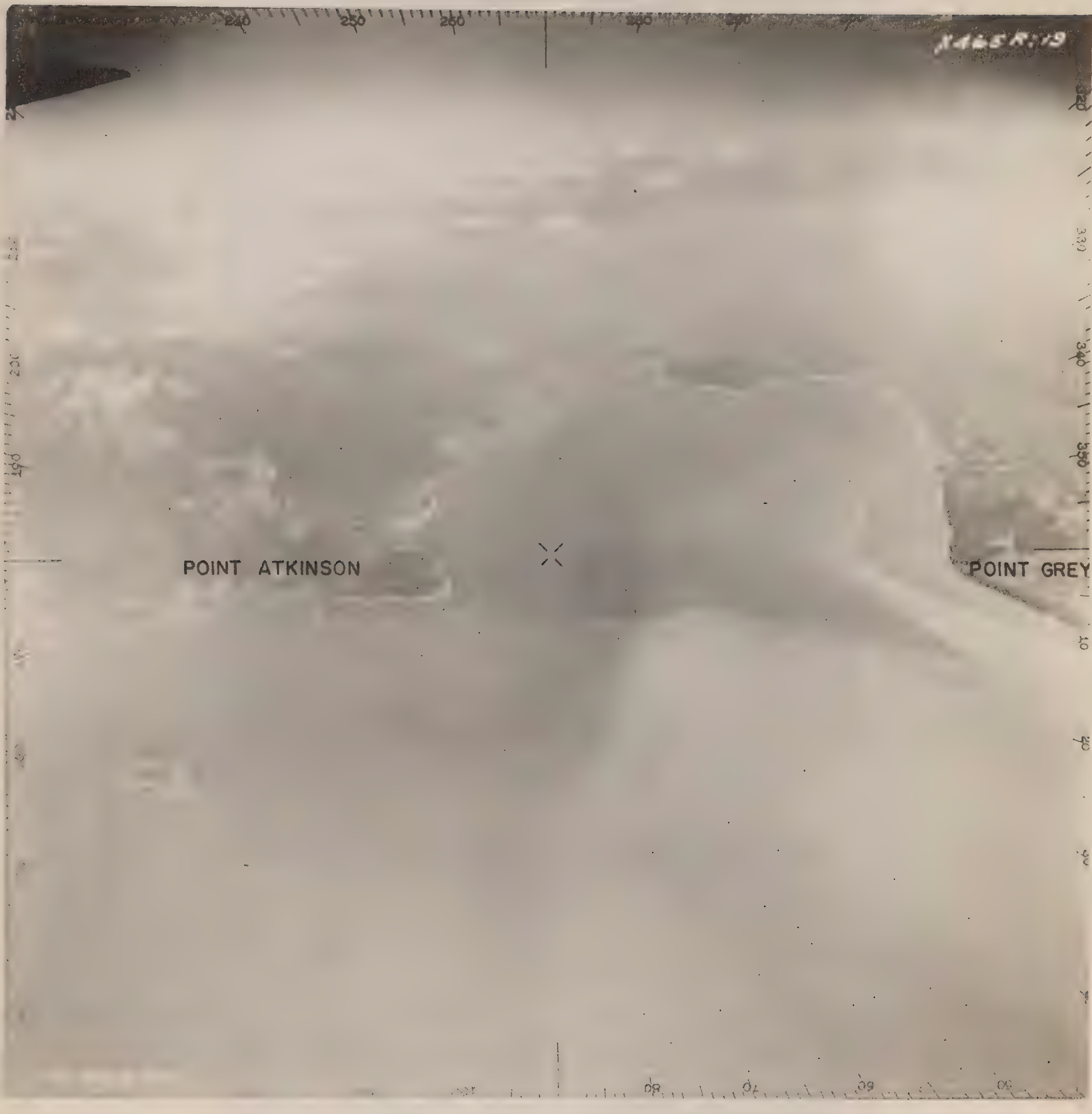

Fig. 13. Oblique photograph taken during end of large ebb 1 June 1950 showing fresh water from North Arm entering Burrard Inlet and also flowing northward.

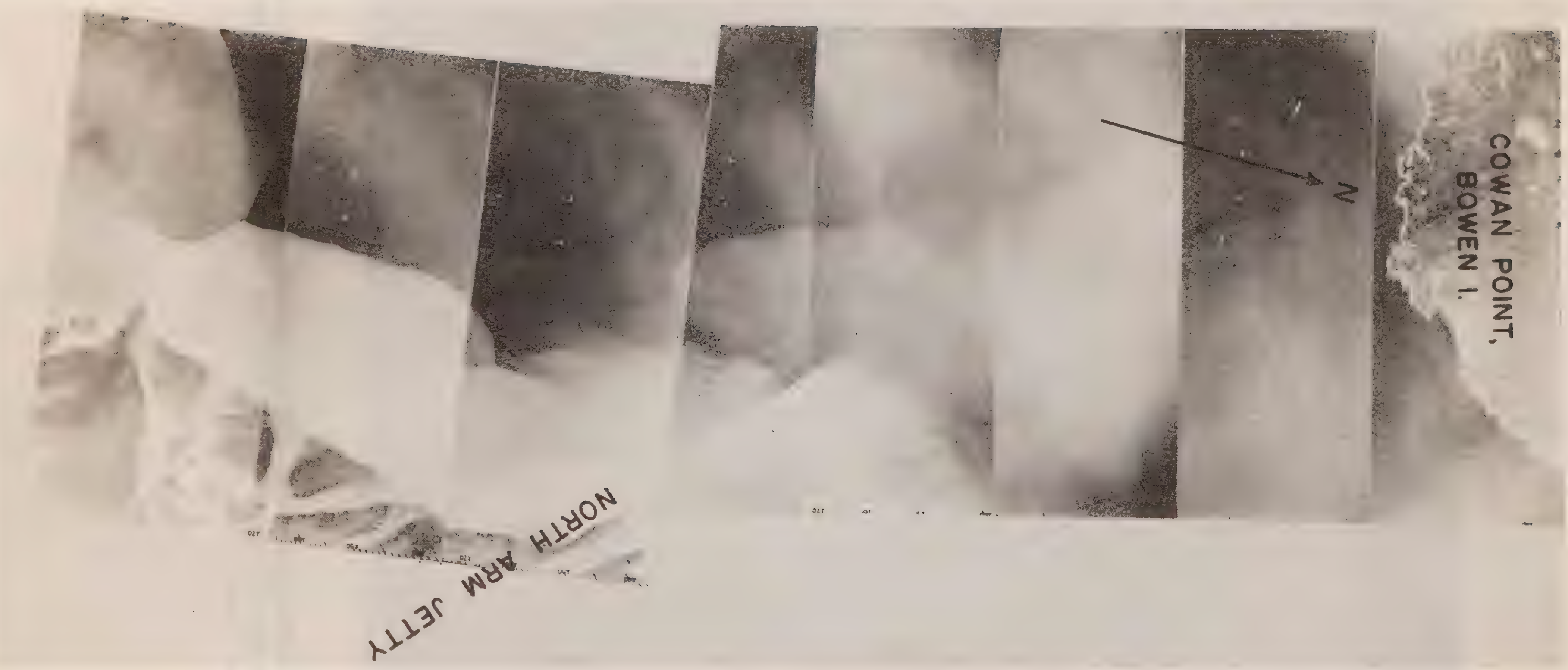

Fig. 14. Mosaic of vertical photographs taken during end of large ebb on 1 June 1950 showing plume from Middle Arm flowing northward.

Fig. 15. Oblique photograph taken during end of large ebb on 1 June 1950 showing plumes from all three Arms of Fraser River.

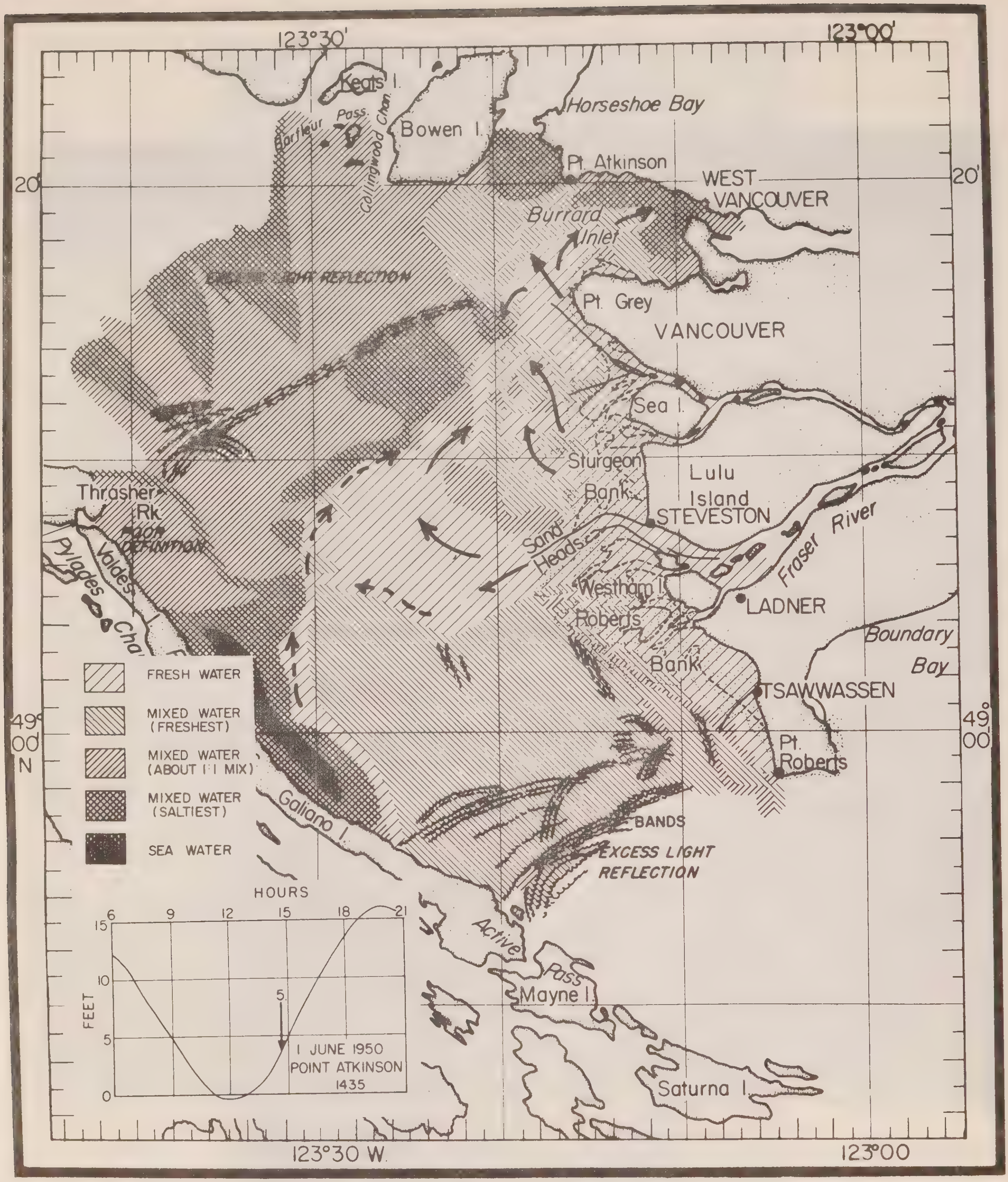

Fig. 16. Distribution of water types in the central Strait of Georgia during the initial stage of large flood on 1 June 1950, as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves (lines represent crest of waves).

Fig. 17. Oblique photograph taken during the initial stage of large flood on 1 June 1950 showing expansion of plume water and of northeastward movement of main plume.

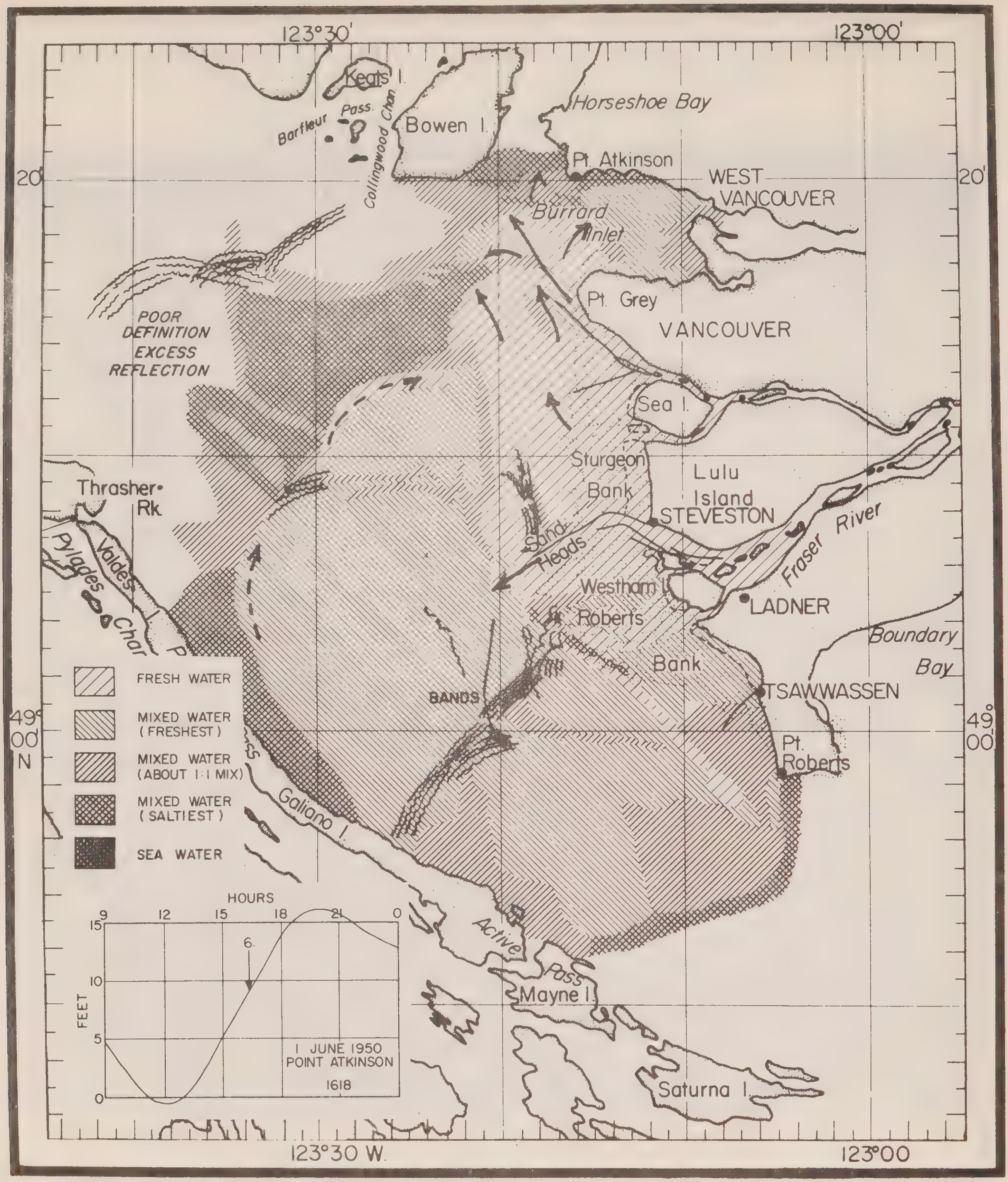

Fig. 18. Distribution of water types in the central Strait of Georgia during halfway along large flood on 1 June 1950 as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves. (lines represent crest of waves).

Fig. 19. Distribution of water types in the central Strait of Georgia during the final stage of large flood on 1 June 1950 as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves. (lines represent crest of waves).

Fig. 20a. Distribution of surface salinity based on oceanographic observations made during 0624-1728, 29 May and 0604-1421, 31 May 1950.

Fig. 20b. Distribution of surface salinity based on oceanographic observations made during 0545-1450, 30 May and 0528-1350, 1 June 1950.

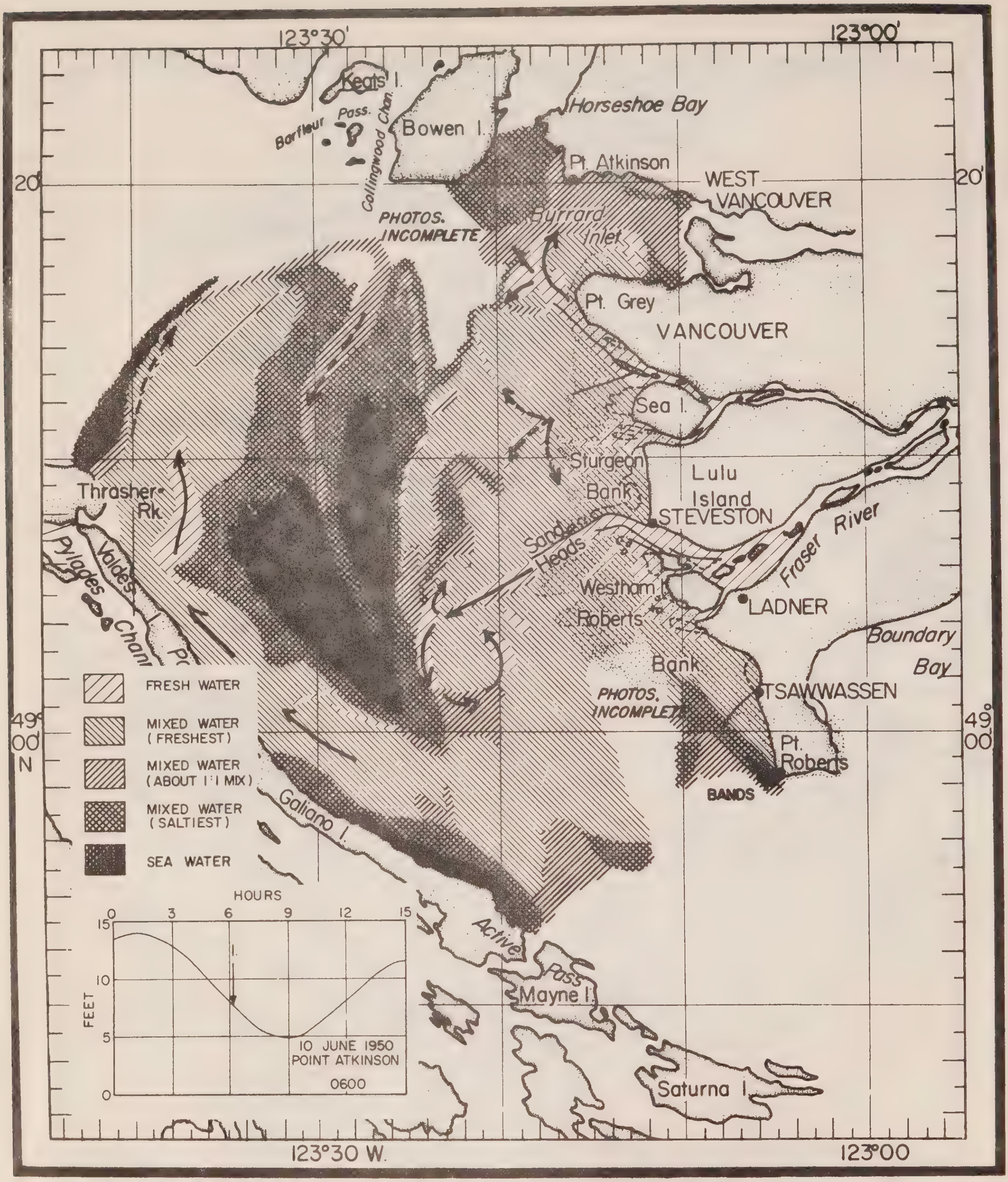

Fig. 21. Distribution of water types in the central Strait of Georgia during halfway along large ebb on 10 June 1950, as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves. (lines represent crest of waves).

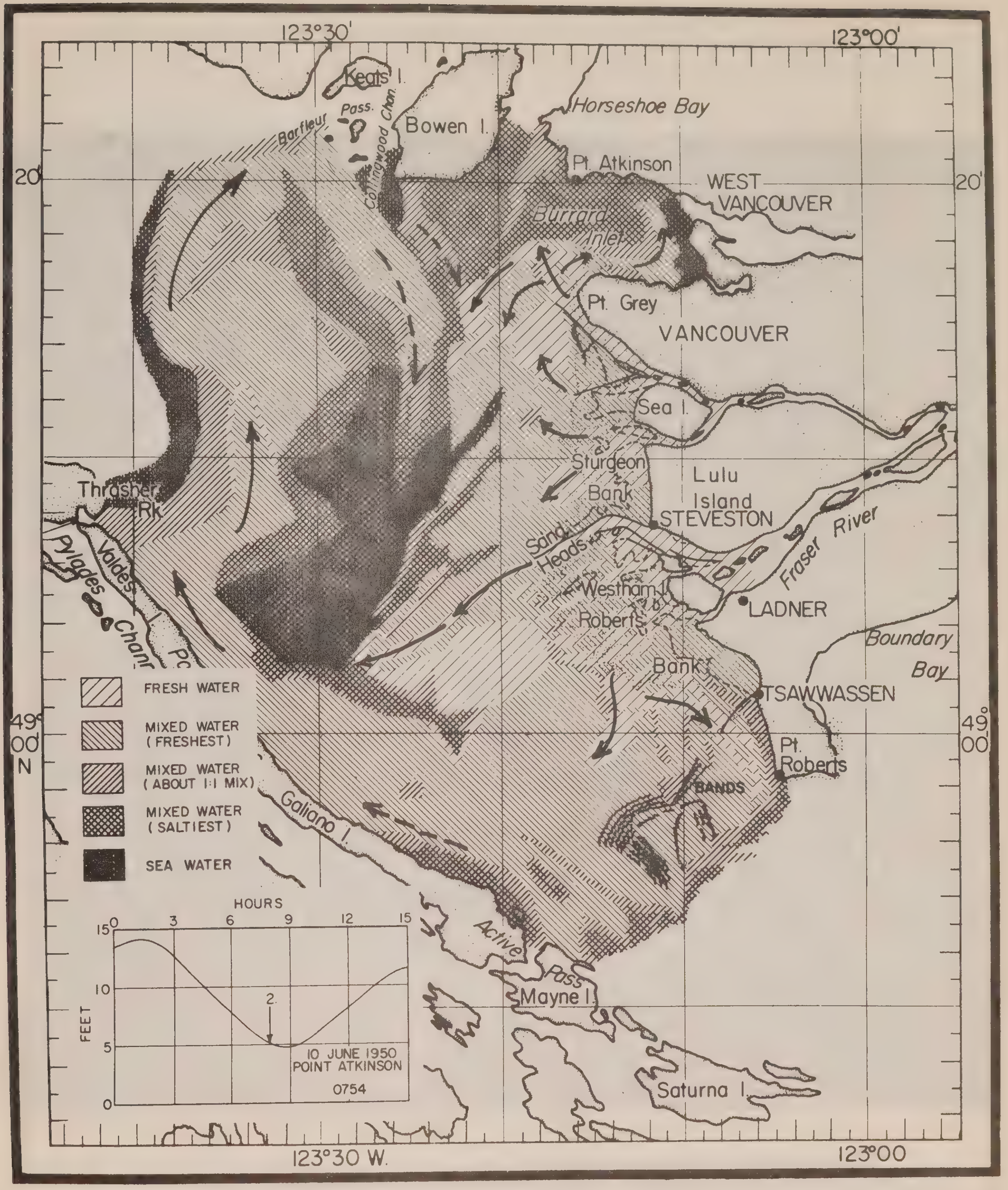

Fig. 22. Distribution of water types in the central Strait of Georgia during final stage of large ebb on 10 June 1950, as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves (lines represent crest of waves).

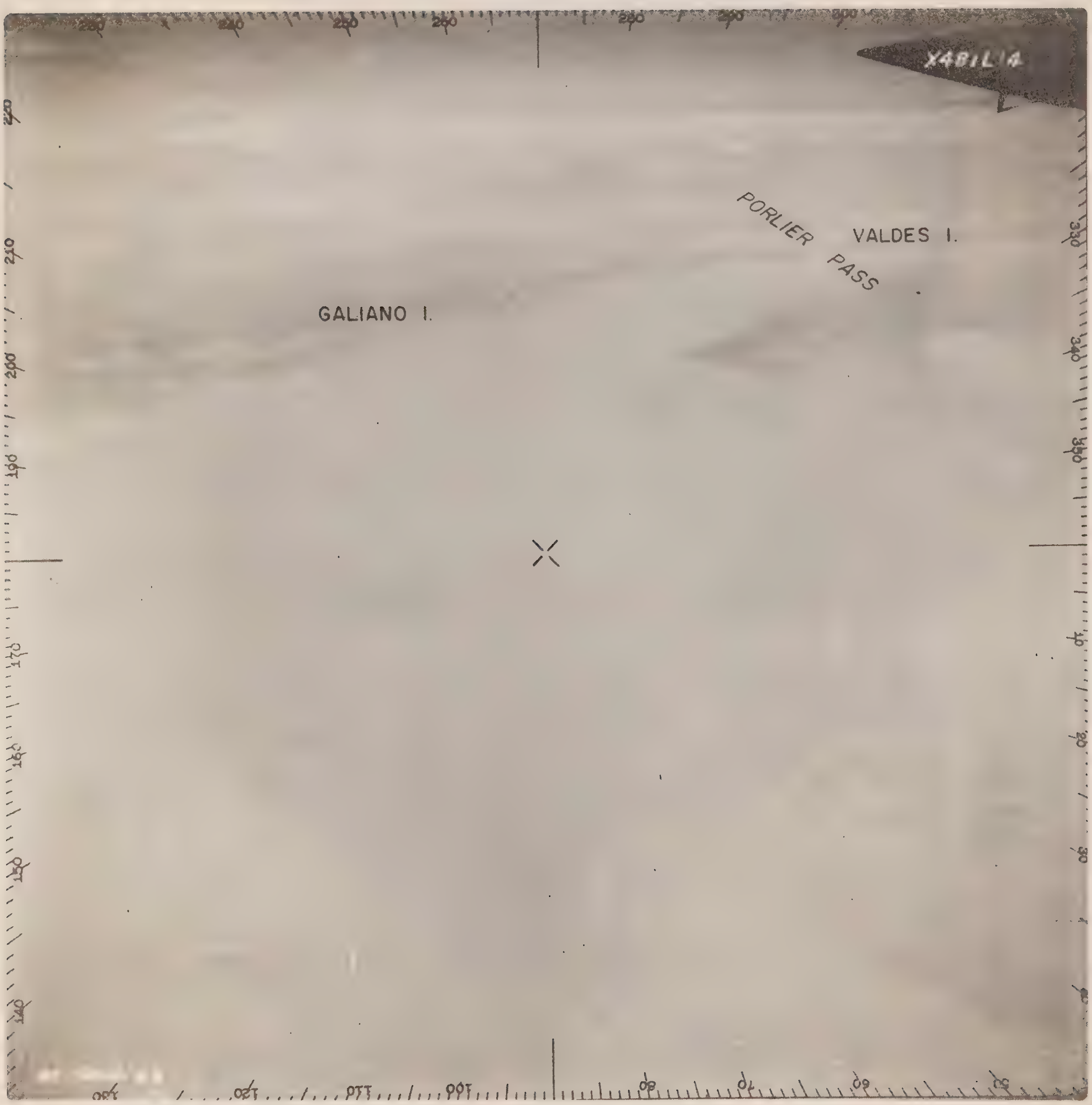

Fig. 23. Oblique photograph taken during final stage of large ebb on 10 June 1950 showing advancing edge of jet-like plume from Main Arm and the fresh water associated with the clockwise loop along the eastern shores of Galiano and Valdes Islands.

Fig. 24. Oblique photograph taken during the final stage of large ebb on 10 June 1950 showing part of the fresh water associated with the clockwise loop veering off Thrasher Rock and directed into mid-strait.

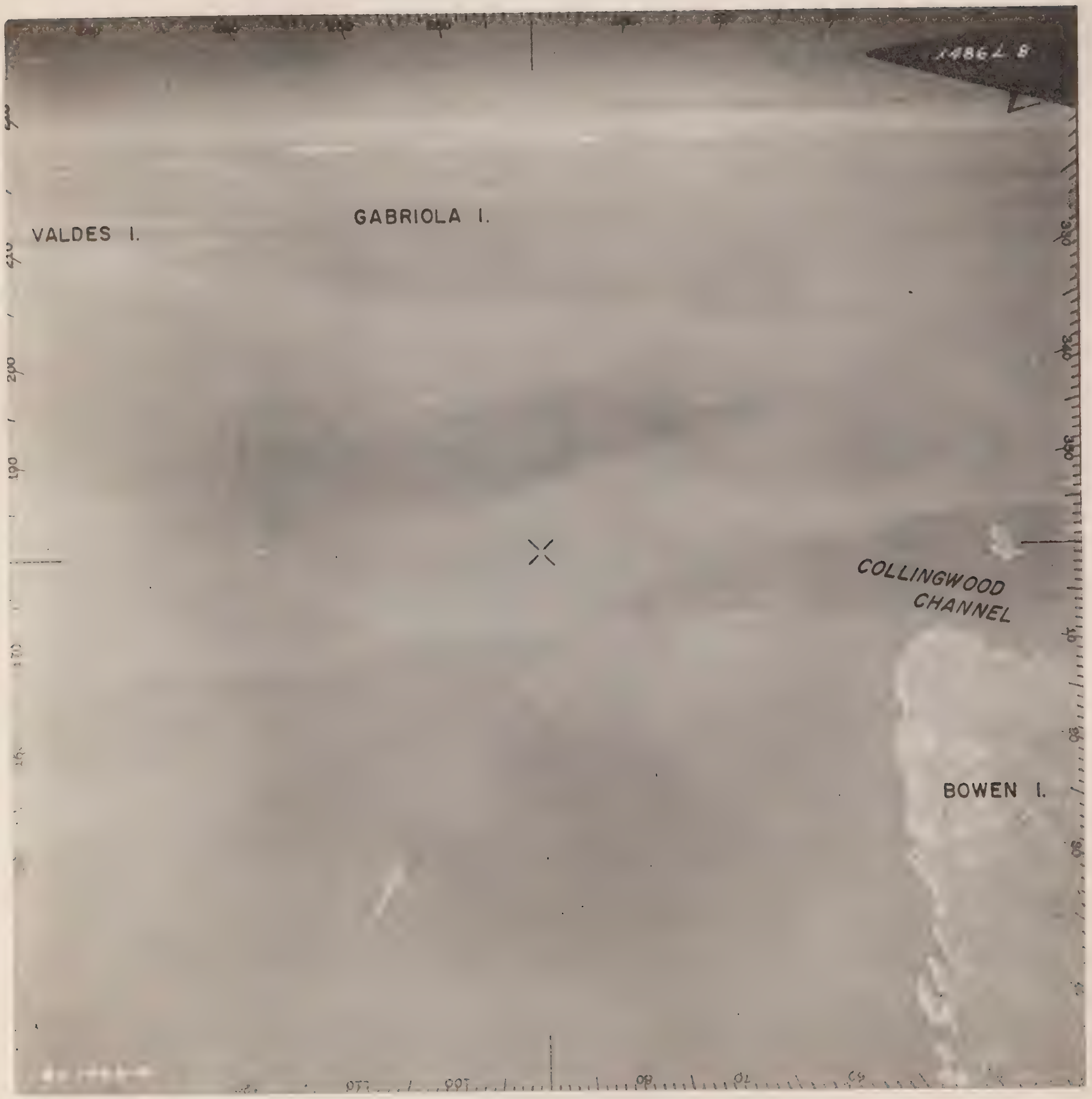

Fig. 25. Oblique photograph taken during the final stage on large ebb on 10 June 1950 showing part of the fresh water associated with the clockwise loop veering further and being directed southward.

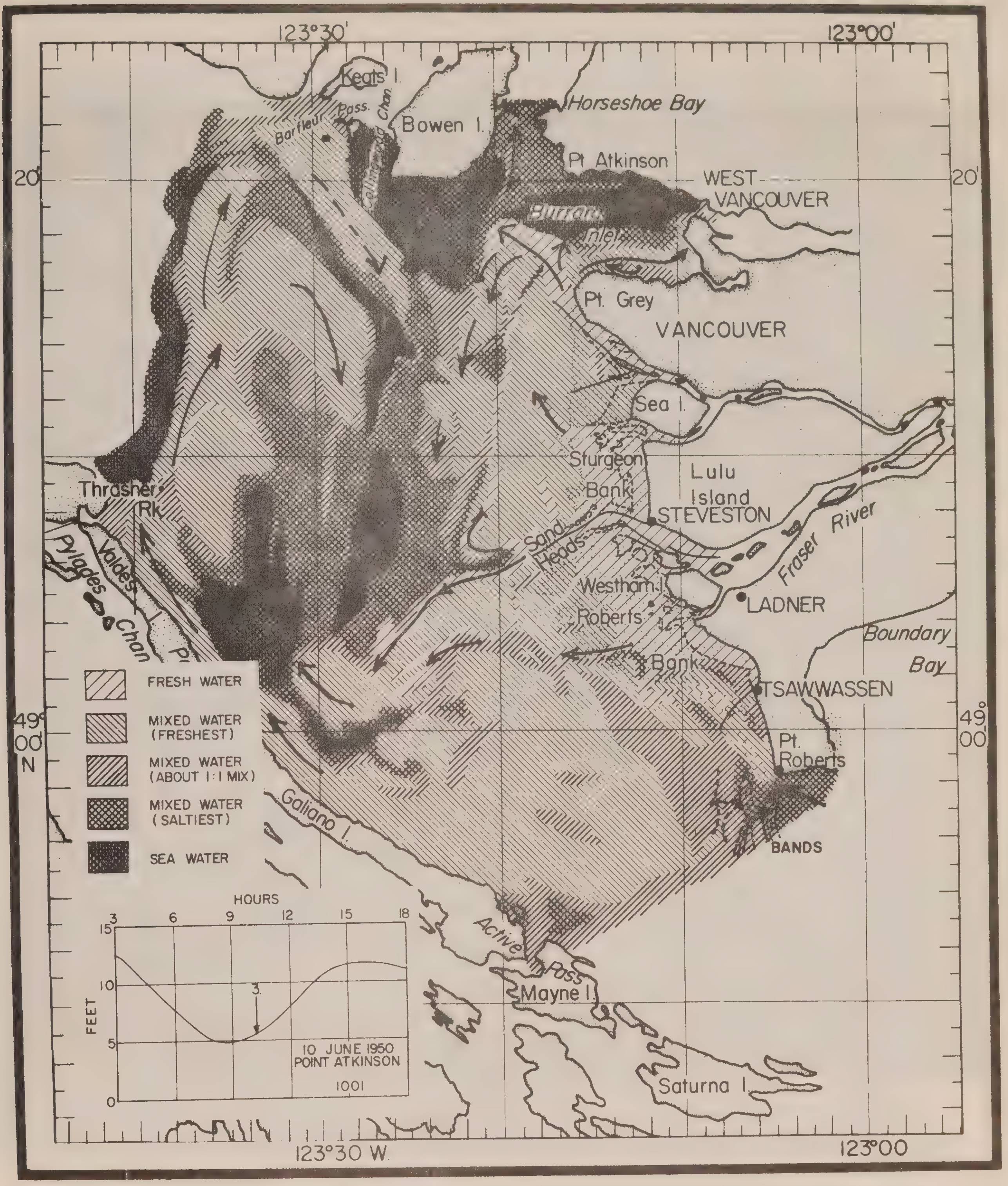

Fig. 26. Distribution of water types in the central Strait of Georgia during the initial stage of large flood on 10 June 1950, as deduced from a series of vertical and oblique aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves(Lines represent crest of waves).

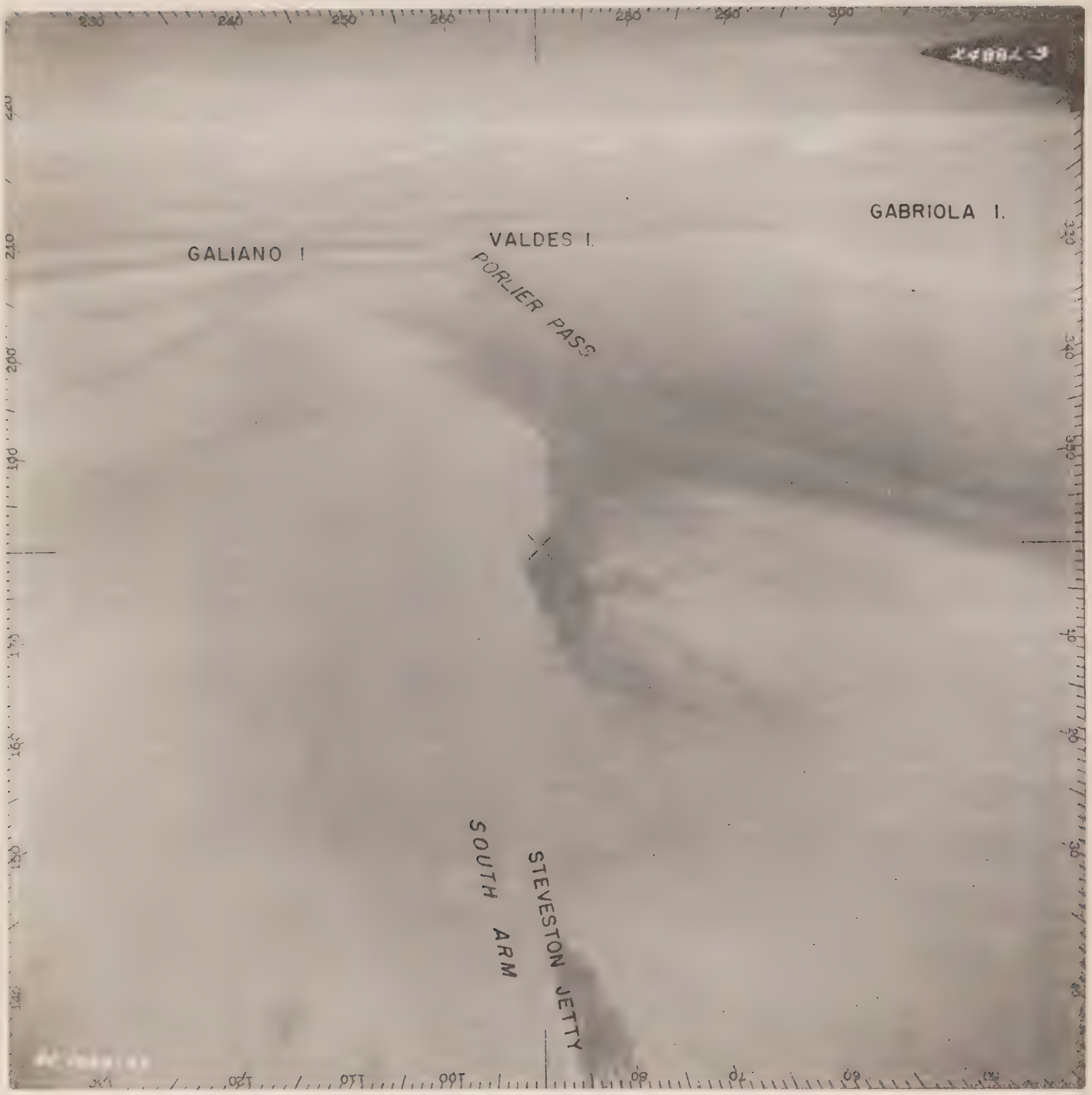

Fig. 27. Oblique photograph taken during the initial stage of large flood on 10 June 1950 showing the well defined jet originating in the Main Arm and the part of the fresh water associated with the clockwise loop.

Fig. 28. Mosaic of vertical photographs taken during the initial stage of large flood on 10 June 1950 showing plumes associated with Middle and North Arms.

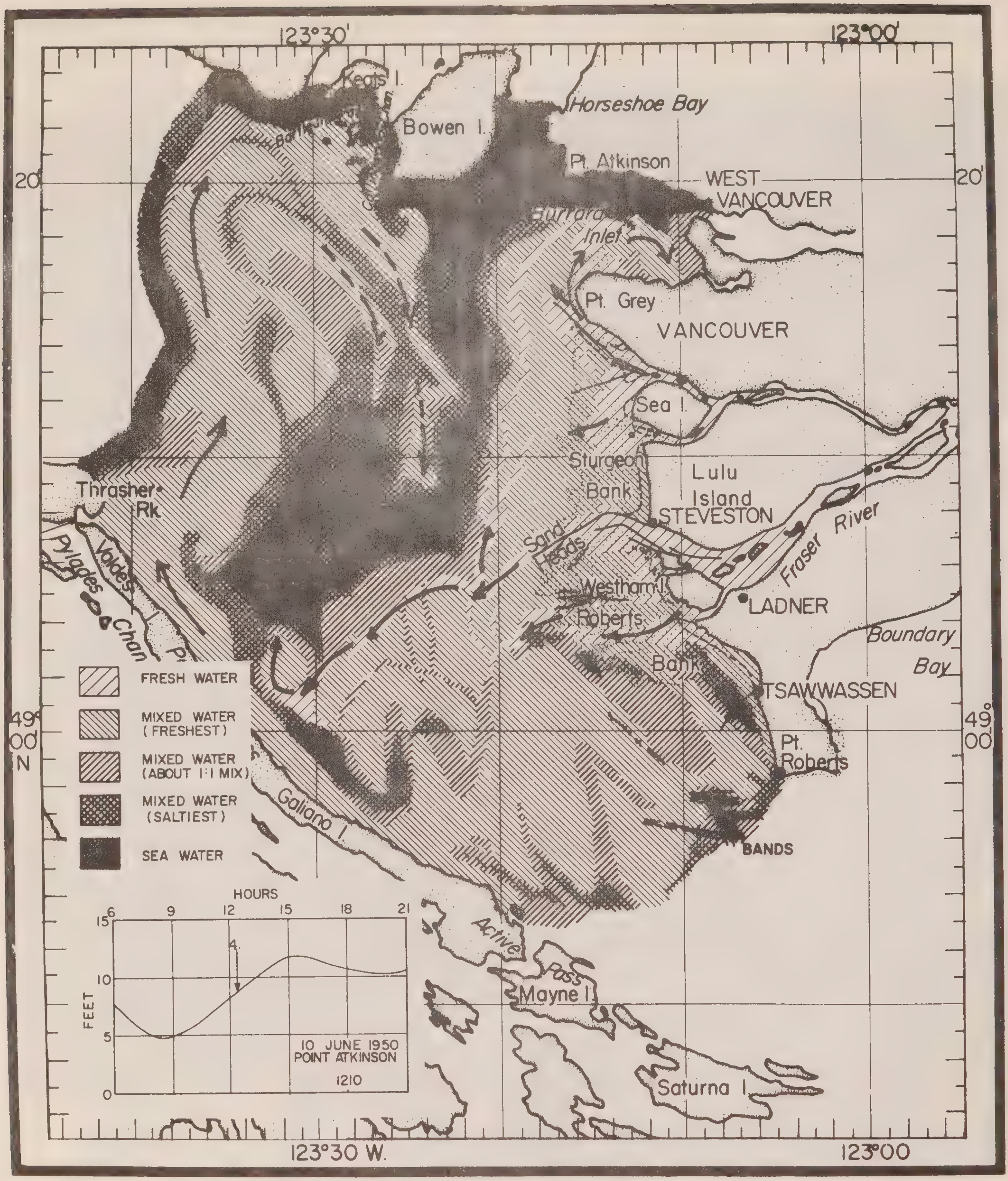

Fig. 29. Distribution of water types in the central Strait of Georgia during halfway along the large flood on 10 June 1950, as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves (lines represent crest of waves).

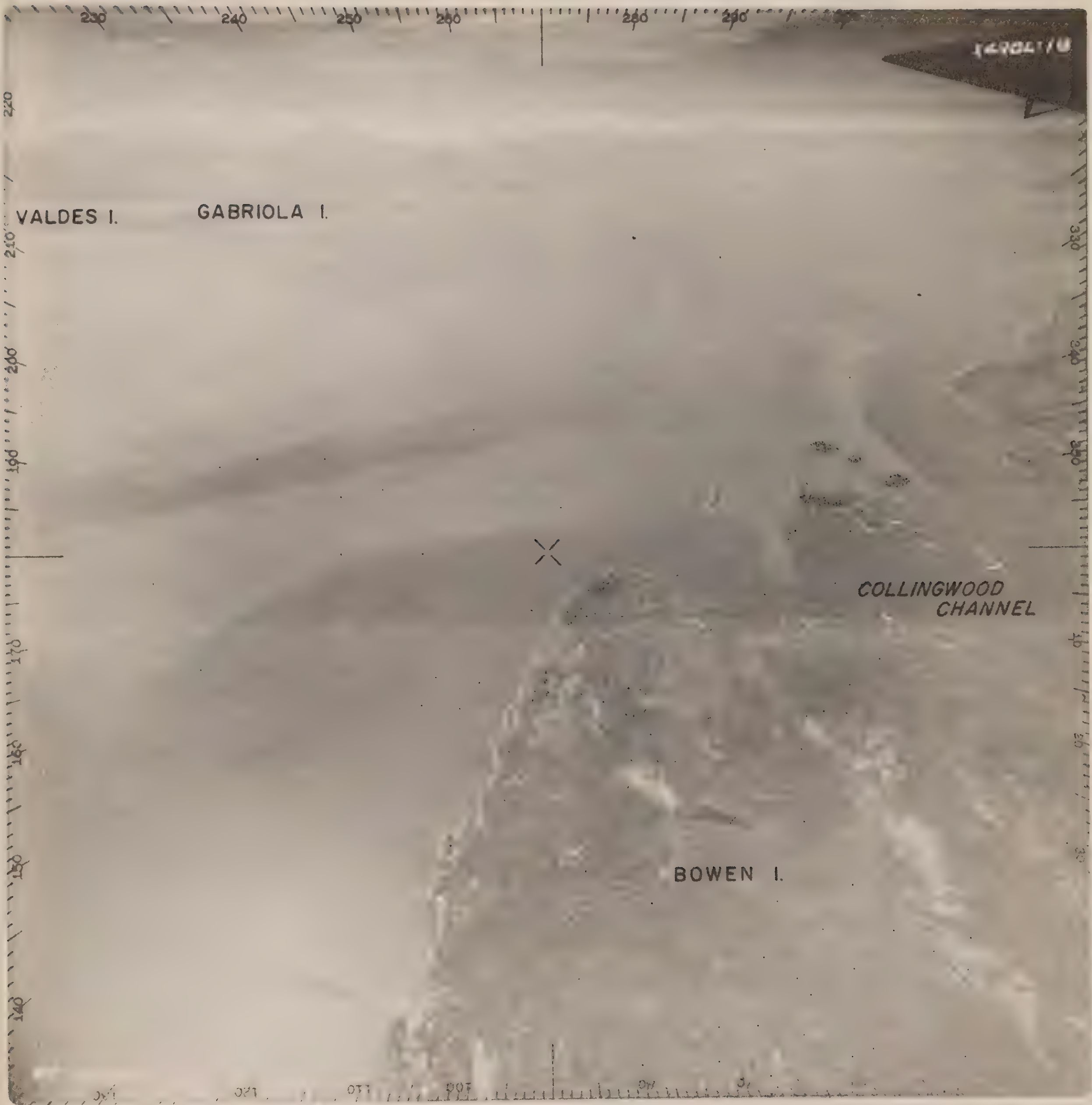

Fig. 30. Oblique photograph taken during halfway along large flood on 10 June 1950 showing the extension of the clockwise loop into Collingwood Channel.

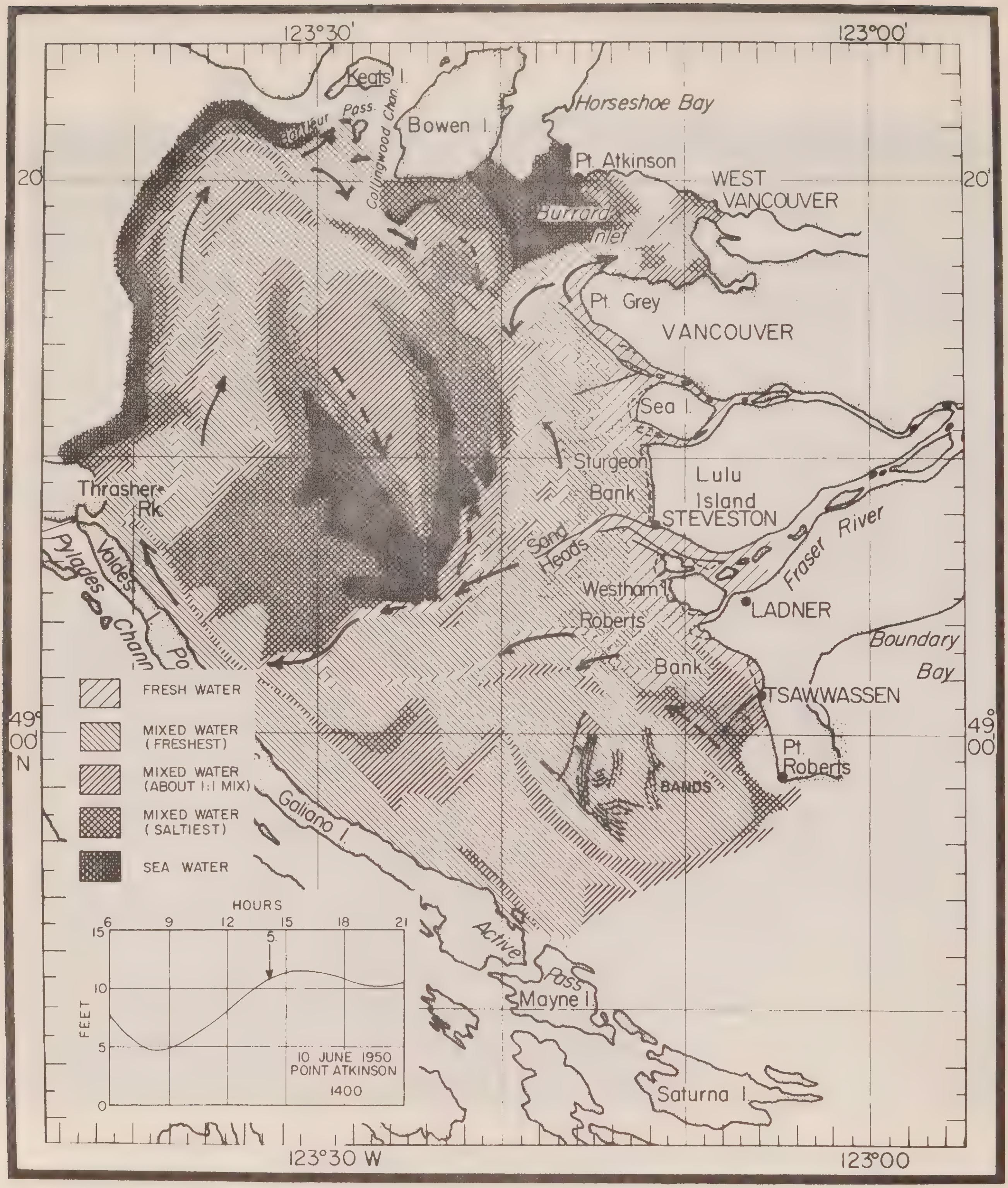

Fig. 31. Distribution of water types in the central Strait of Georgia during the final stage of large flood on 10 June 1950 as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also, but in which there is less certainty with directions than indicated by solid arrows. Brands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves (lines represent crest of waves).

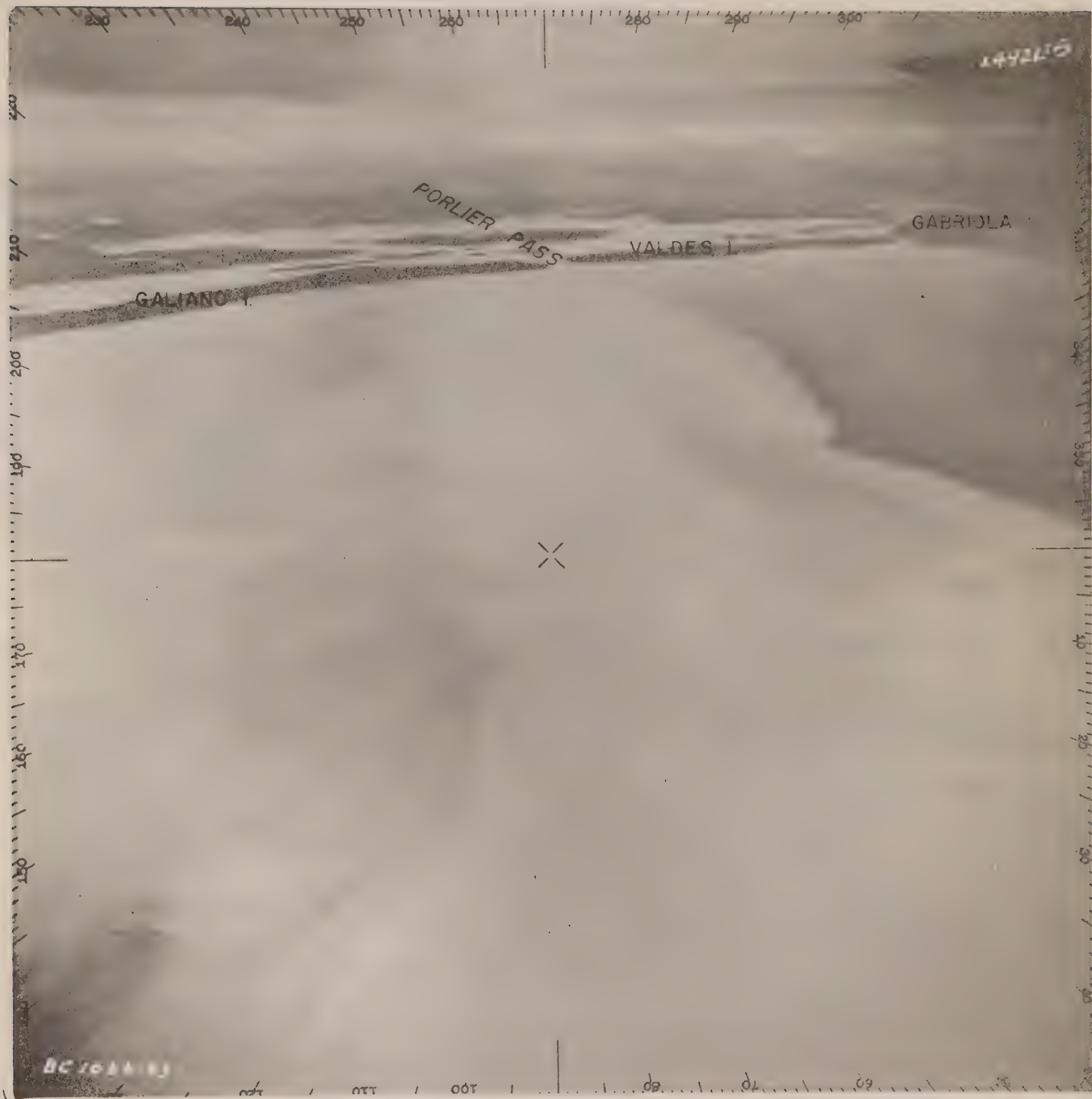

Fig. 32. Oblique photograph taken during the final stage of large ebb on 10 June 1950 showing the advancing edge of the main jet-like plume merging with the fresh water already lying off Porlier Pass. A convergence line is evident where the two bodies of water meet.

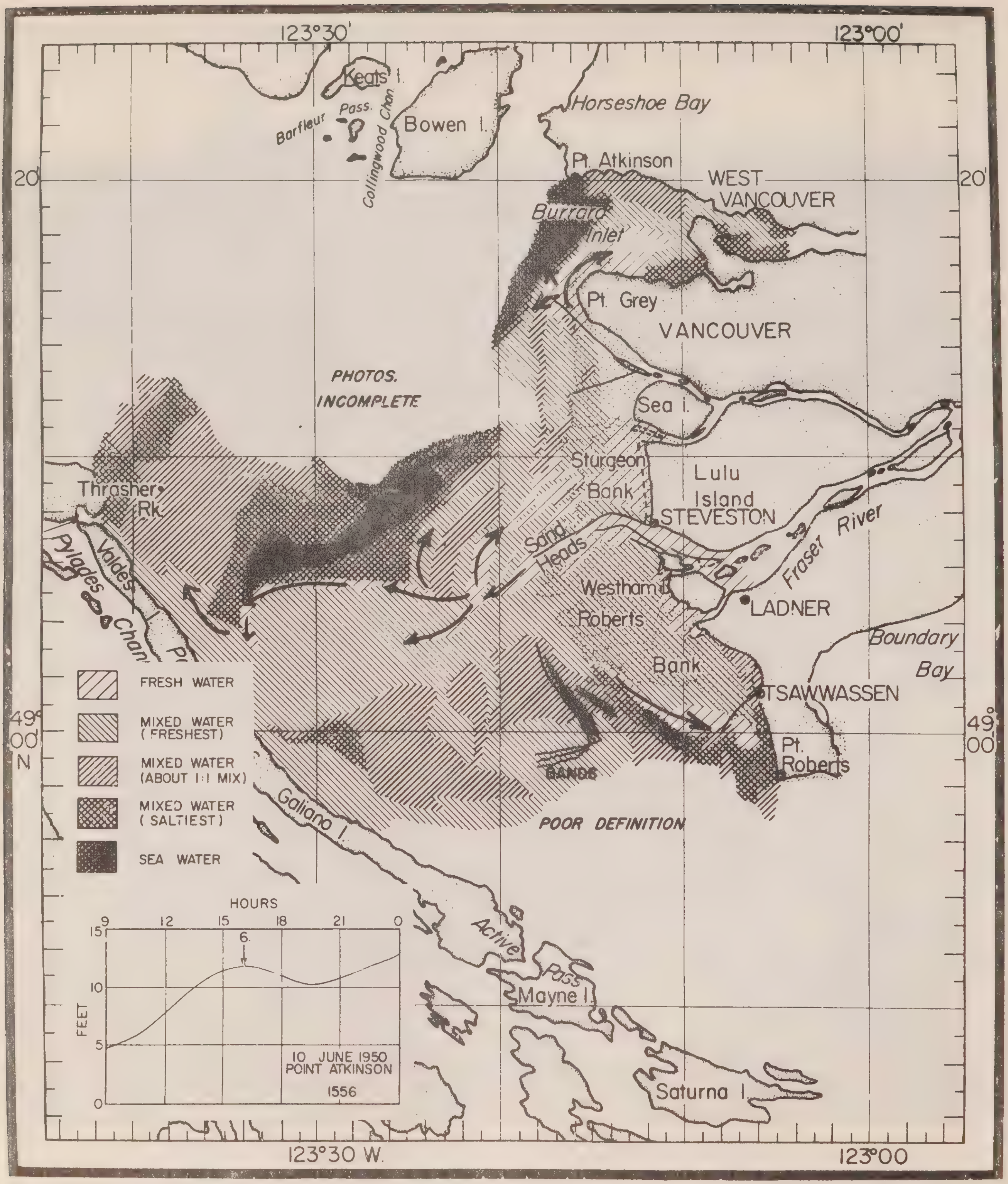

Fig. 33. Distribution of water types in the central Strait of Georgia during the initial stage of small ebb on 10 June 1950, as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows. Bands denote alternate bands of ruffled and smooth water surface indicating the presence of internal waves (lines represent crest of waves).

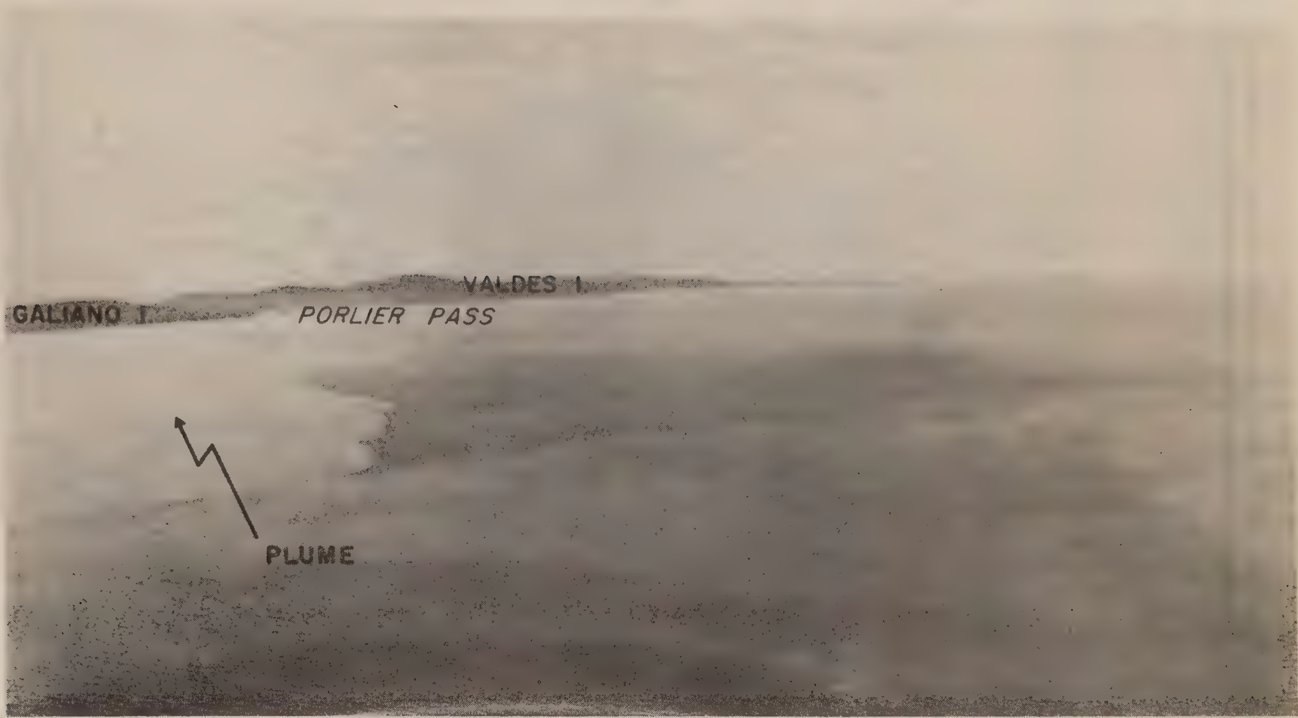

Fig. 34a. Oblique photograph taken by a hand-held camera during halfway along large ebb on 4 June 1968 showing brackish water lying off northern end of Galiano Island and along Valdes Island.

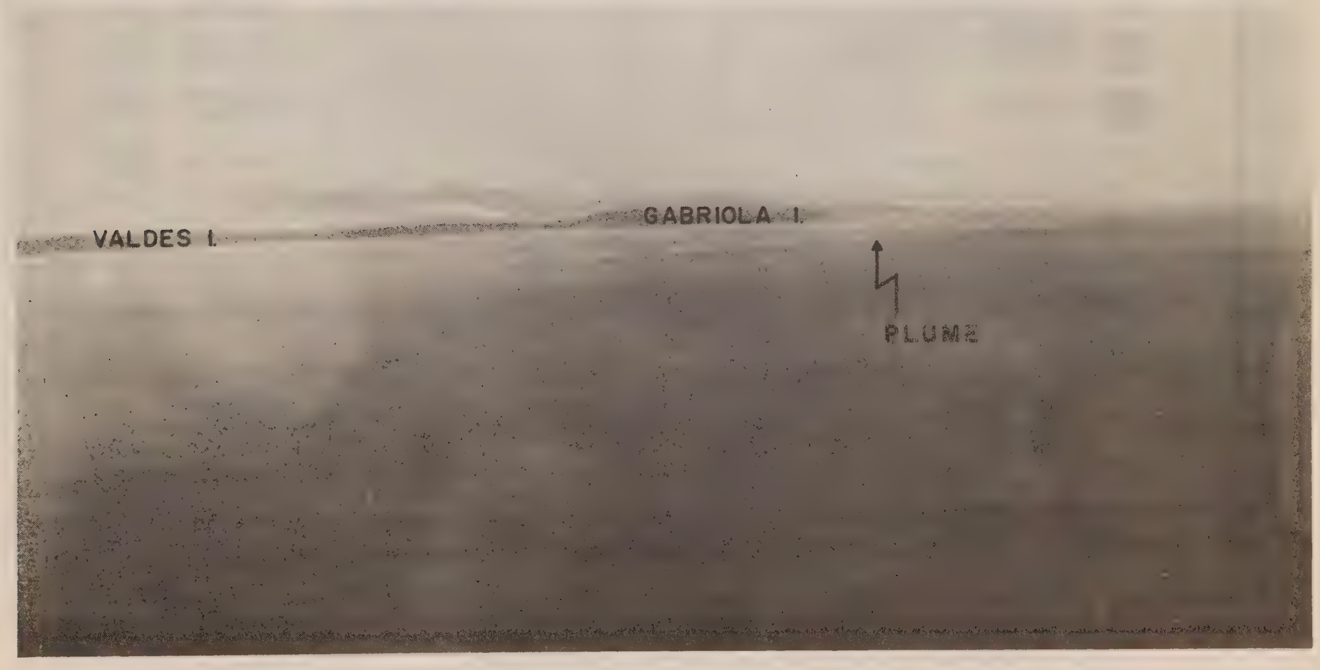

Fig. 34b. Oblique photograph taken by a hand-held camera during halfway along large ebb on 4 June 1968 showing brackish water lying off Valdes Island. The feature of this water is similar to that associated with that of the clockwise loop observed in earlier photographs.

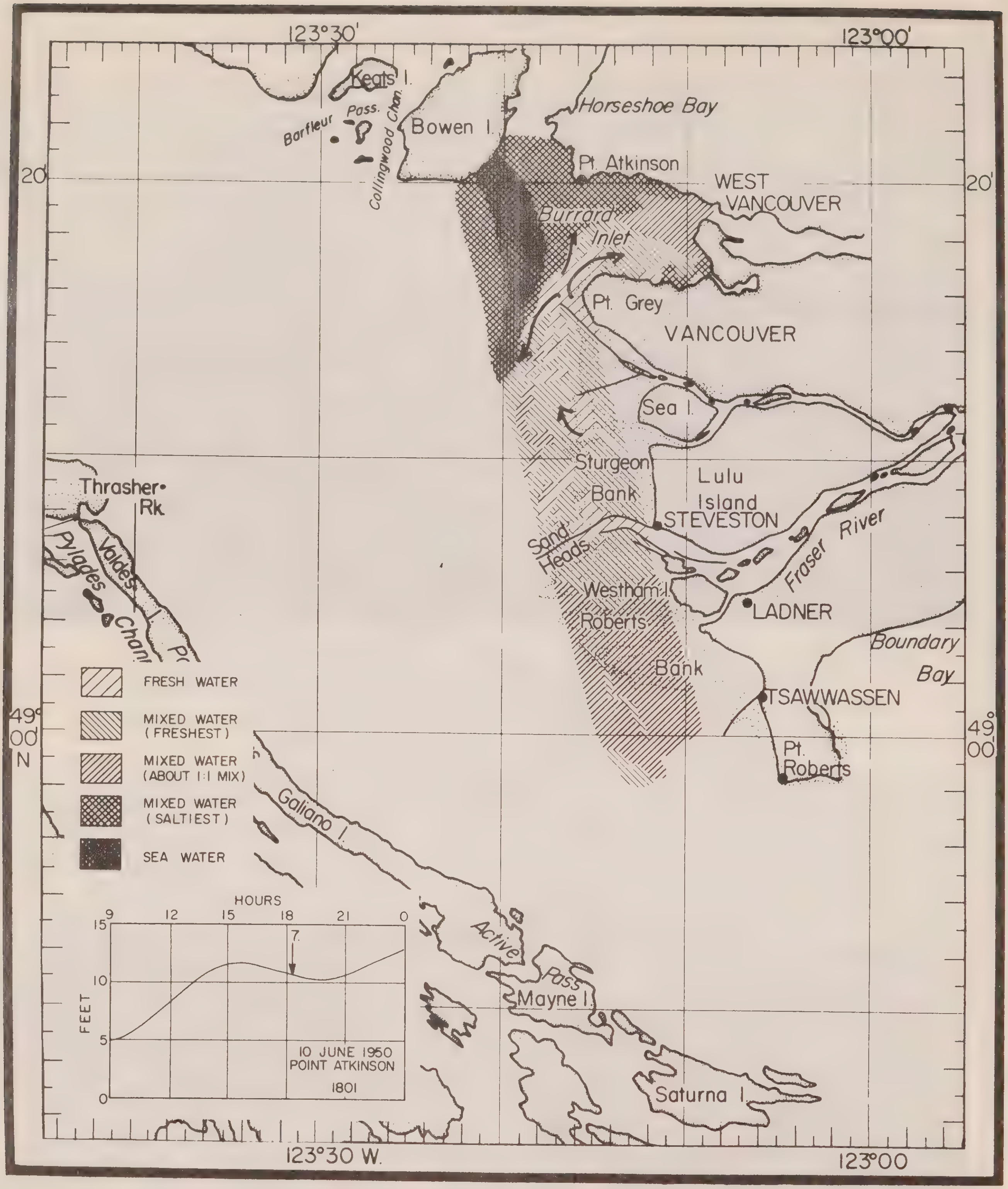

Fig. 35. Distribution of water types in the Central Strait of Georgia during halfway along small ebb on 10 June 1950, as deduced from a series of vertical aerial photographs. Oblique photographs were not available. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows.

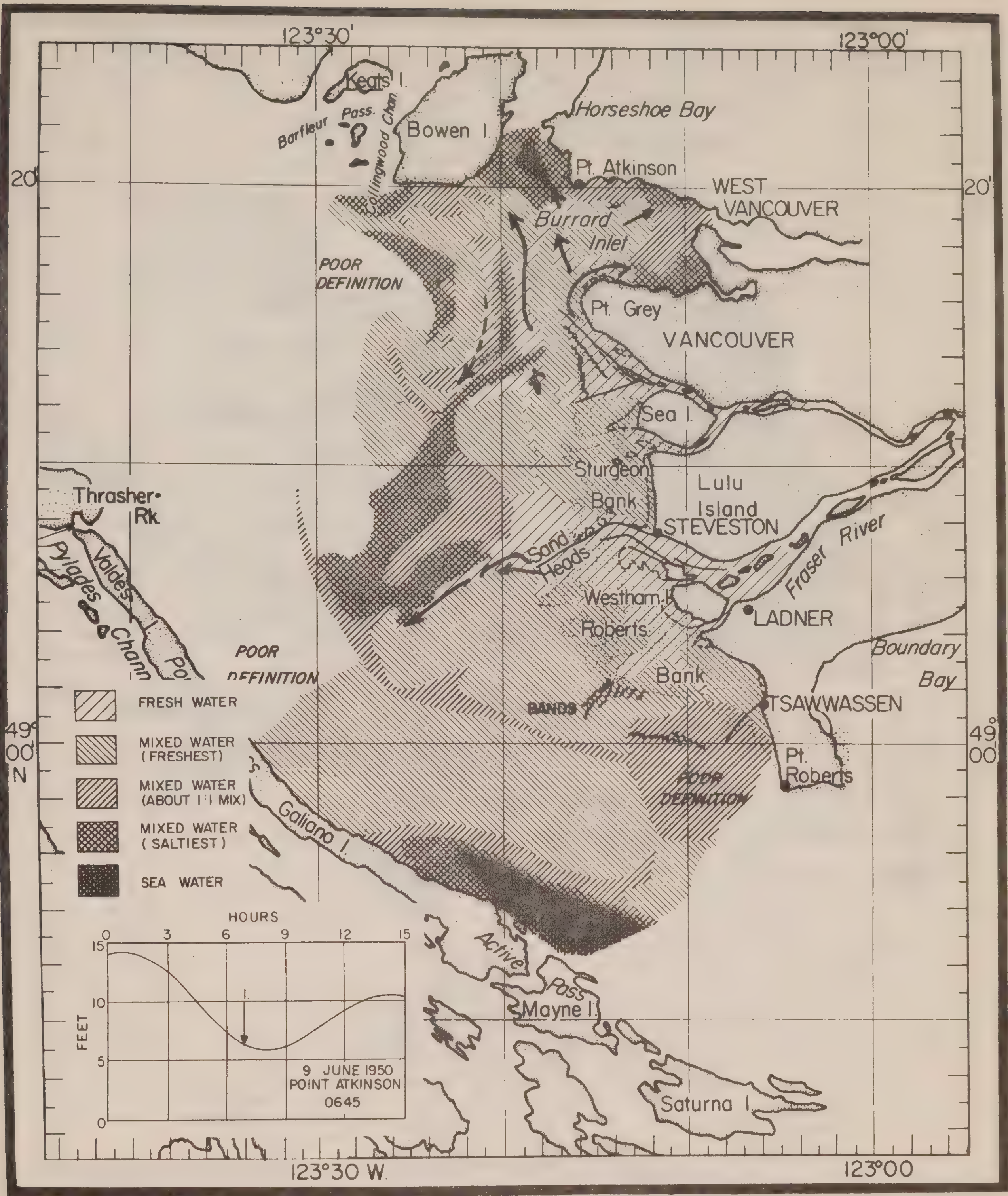

Fig. 36. Distribution of water types in the central Strait of Georgia during the final stage of large ebb on 9 June 1950, as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted direction of surface current; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows.

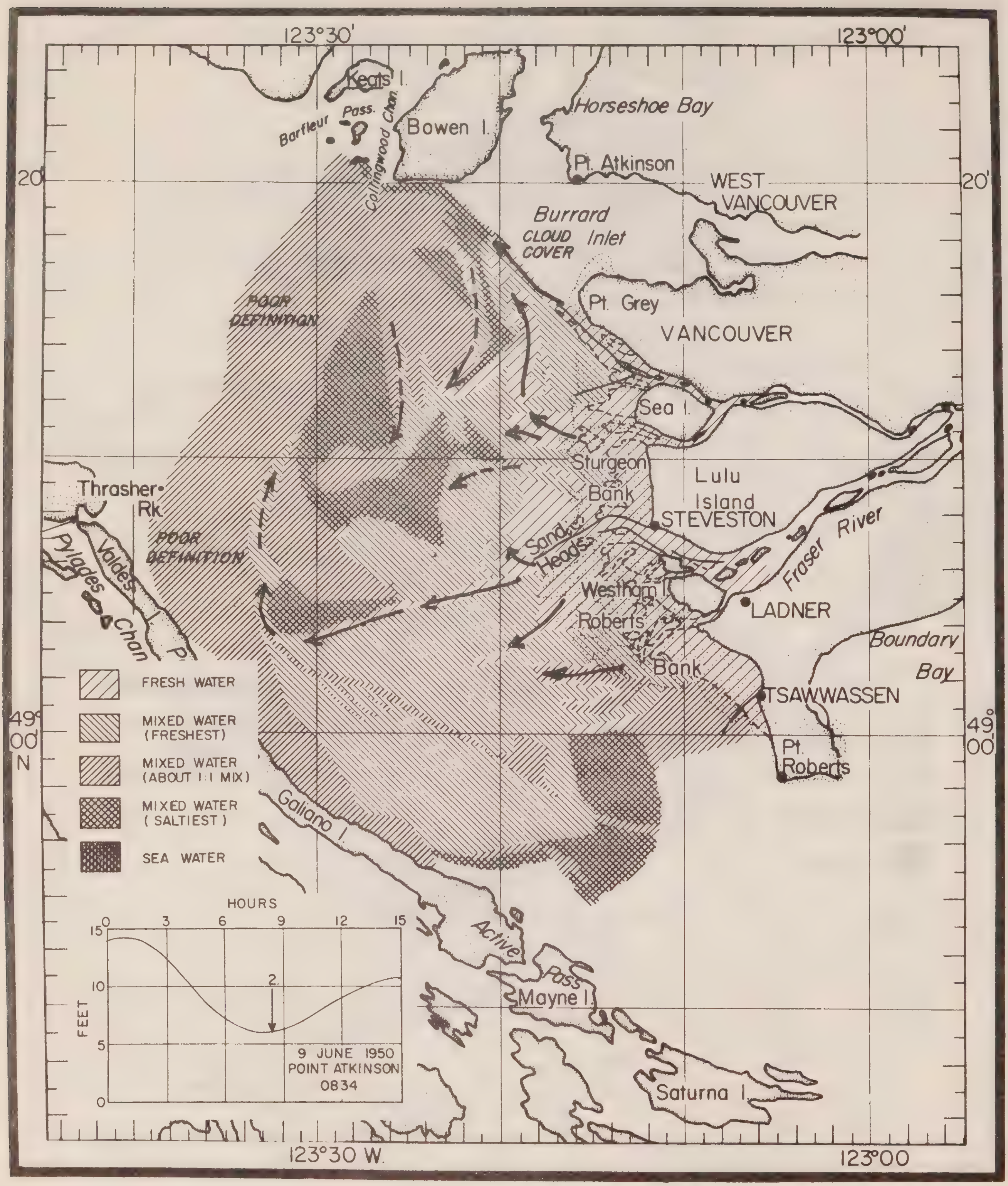

Fig. 37. Distribution of water types in the central Strait of Georgia during the initial stage of large flood on 9 June 1950, as deduced from a series of vertical and horizontal aerial photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows.

Fig. 38a. Distribution of surface salinity based on oceanographic observations made during 0523-1440, 13 June 1950.

Fig. 38b. Distribution of surface salinity based on oceanographic observations made during 0532-1451, 14 June 1950.

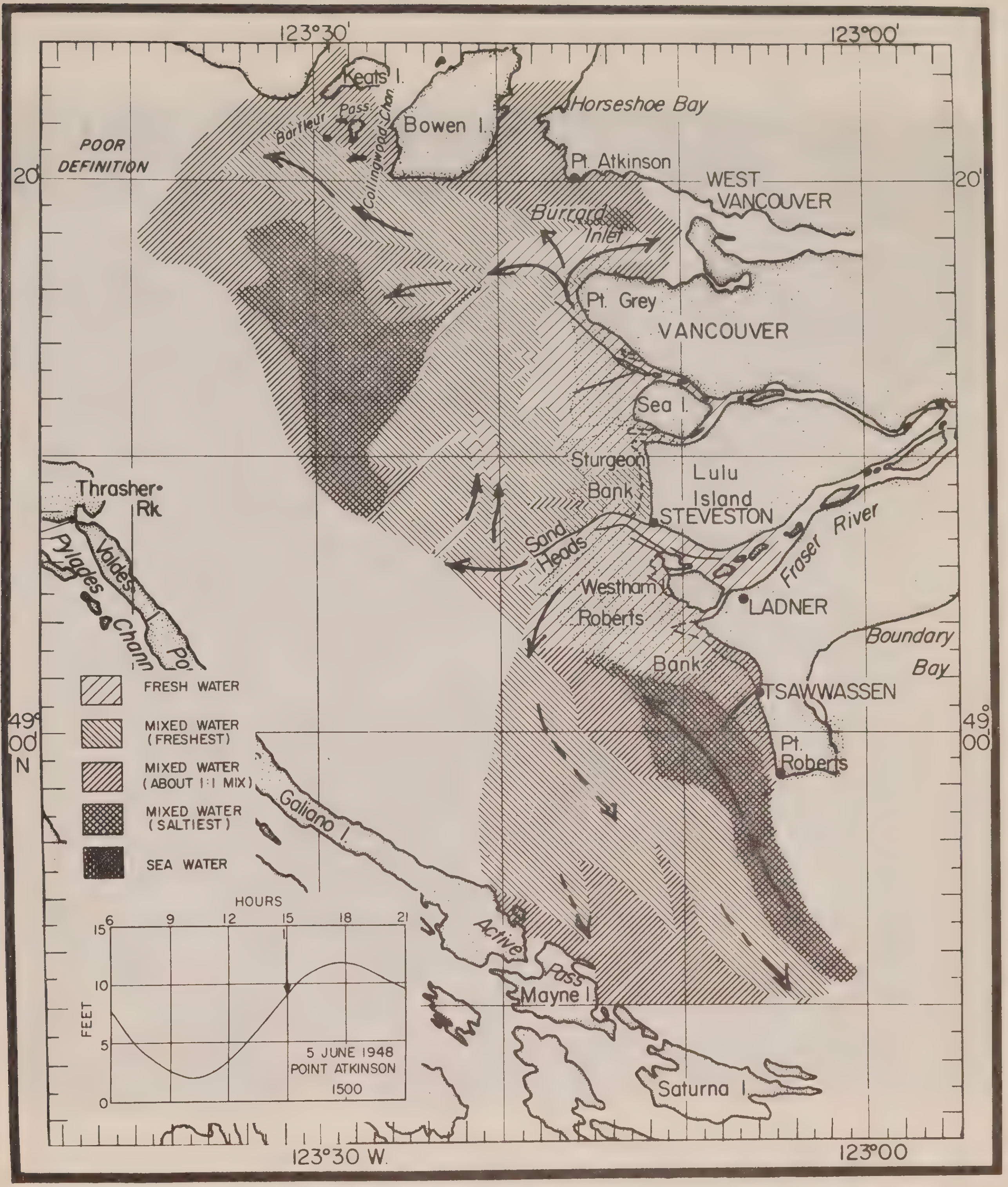

Fig. 39. Distribution of water types in the central Strait of Georgia during the final stage of large flood on 5 June 1948, as deduced from two oblique photographs. Solid arrows denote interpreted directions of surface currents; broken arrows denote directions of surface currents also but in which there is less certainty with directions than indicated by solid arrows.

Fig. 40. Oblique photograph taken during the final stage of large flood on 5 June 1948 showing the northern extension of Fraser River water.

Fig. 41. Oblique photograph taken during the final stage of large flood on 5 June 1948 showing the southern extension of Fraser River water.